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Traffic Accident Data, Driver Performance, and Motor Vehicle Update

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The Nature and Causes of the 1982 Traffic Accident Casualty Reductions in British Columbia

PETER J. COOPER

ABSTRACT

The extent of the 1982 traffic accident casualty reduction in British Columbia has been evaluated and found to be beyond what could be expected from chance fluctuation alone. The greatest changes were found in casualty-producing accidents involving young drivers, especially during the nighttime. These accidents were seemingly independent of alcohol use. Given this initial determination, the possible external causes for the decrease have been examined with the result that economic factors alone can be shown to account for a large part of the effect, although for a significant portion of the change, there is as yet no ready explanation. The most important conclusion arising from the analysis is that should economic conditions improve, a concomitant rise in traffic casualties can be expected unless mitigated by significant safety program interventions.

A comparison of 1982 statistics on traffic accidents in British Columbia with those for 1981 indicates a dramatic and welcome change. Total accidents decreased approximately 12 percent while injuries and fatalities decreased 23 and 30 percent, respectively. A similar effect was observed throughout Canada but British Columbia showed the greatest reduction, partially as a consequence of its high 1981 ranking. The question, of course, is why? What happened during 1982 to cause the accident and casualty reductions--was it a change in travel patterns or a change in safety attitudes? In this paper, an attempt is made to cast some light on the controversy.

THE NATURE OF THE EFFECT

The overall accident statistics (1,2) for 1981 and 1982 are as follows:

	1981	1982	Change (%)
Fatal accidents	761	524	-31
Injury accidents	30,626	23,662	-23
Property-damage-only (PDO) accidents	96,444	87,682	-9
Deaths	859	601	-30
Injuries	44,123	33,807	-23

Because the greatest changes are apparent in injury and fatal accidents or casualties, they form the primary focus for this paper. Casualties have been chosen as the best historical index because they represent a somewhat greater sample size than casualty-producing accidents and form one of the statistics normally employed in epidemiological studies.

Figure 1 shows the 1982 casualty reductions set against the monthly totals for previous years. A fairly consistent seasonal fluctuation is evident

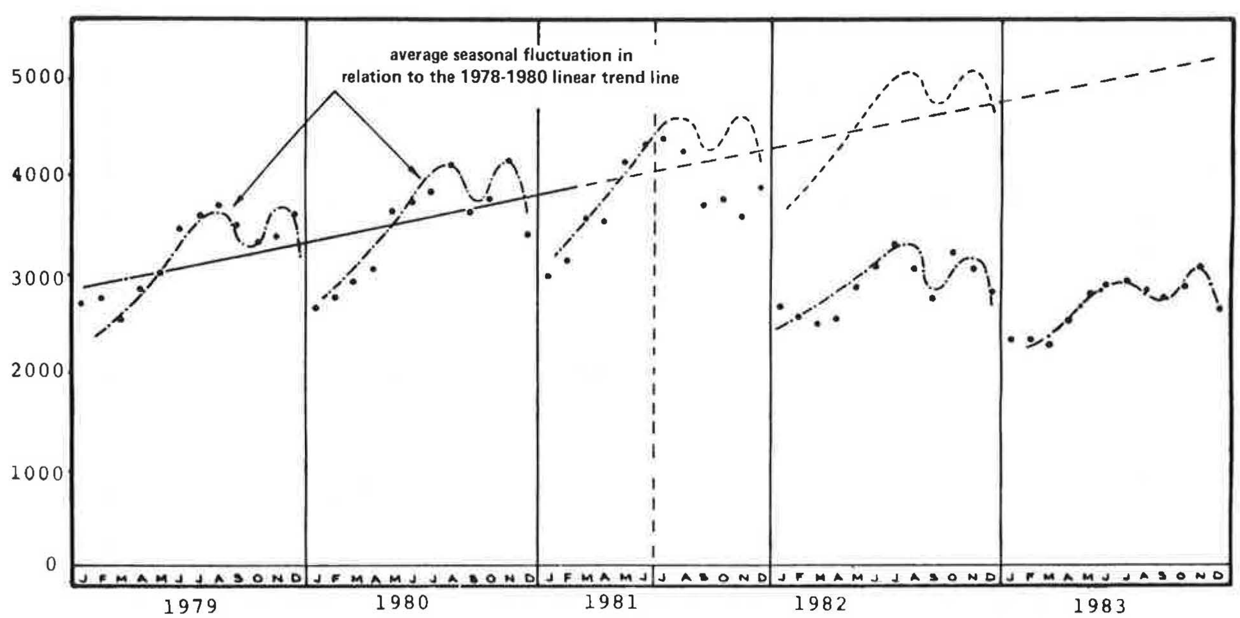


FIGURE 1 Historical traffic accident casualty trends in British Columbia.

from the 1979-1980 data and this has been superimposed on the upward trend line established by using the 1979 and 1980 information.

The first issue to address is whether or not the 1982 reduction is significant and when the reduction actually commenced. This can be accomplished fairly simply. An examination of Figure 1 would lead one to suspect that the decline in casualties actually commenced about halfway through 1981. Using the Box-Jenkins technique to project expected values for 1982 based on the time series for the previous 5 years, there was a marginally significant difference found between actual and projected values (X^2 probability of .08). The time series before 1982 is not entirely devoid of other events, however, such as periodic seat belt wearing campaigns and driving-while-intoxicated (DWI) blitzes, which may affect the significance assessment of the 1981-1982 reduction. In using analysis-of-variance techniques to test the 1979-1982 casualty data, which is grouped by half-year periods, it was learned that the reduction occurring between the first half of 1982 and

data by half year period

Dependent variable - casualties

Anova Summary Table

Source of Variation	DF	Sum of Squares	Mean Squares	F	Significance Level
Between groups	8	11466192.593	1433274.074	13.372	0.000
Within groups	45	4823283.333	107184.074		
Total	53	16289475.926			

Group Statistics

Group	Codes & Labels		N	Mean	SD
Group 1	- 01-06	1979	6	2913.333	292.757
Group 2	- 07-12		6	3520.000	136.088
Group 3	- 13-18	1980	6	3108.333	461.841
Group 4	- 19-24		6	3801.667	293.081
Group 5	- 25-30	1981	6	3598.333	530.638
Group 6	- 31-36		6	3915.000	314.372
Group 7	- 37-42	1982	6	2703.333	225.891
Group 8	- 43-48		6	3033.333	213.698
Group 9	- 49-54	1983	6	2548.333	290.063

T-Test Between Group Means - (Values of p are for a two-tailed test)
Note: Statistics are only printed if p is less than or equal to .050

Statistics	Groups
t = 2.592 p = .028	Group 3 Group 5
t = 4.735 p = .001	Group 5 Group 7
t = 4.664 p = .001	Group 6 Group 8

Only comparisons involving equivalent time periods in successive years are shown above

FIGURE 2 Comparison of half-year period casualty totals, 1979-1983.

the first half of 1981, and between the second half of 1982 and the second half of 1981, were statistically significant at the .001 level (see Figure 2). The 1982 casualty decrease is thus a real effect that cannot be attributed to chance alone and, from a visual examination of the monthly figures in comparison with the seasonal fluctuations and the trend line established from the 1979-1980 data, it can be postulated that this decrease actually commenced at approximately the midpoint of 1981.

ASSESSMENT OF POSSIBLE CAUSES

There have been a number of suggested contributory causes for the effects that have just been observed. Some of these, together with an assessment of their applicability, are as follows:

1. A Change in Vehicle Occupancy--For 1981 and 1982, we can calculate both fatality-to-fatal accident and injury-to-injury accident ratios. These are 1.13 and 1.44, respectively, for 1981, and 1.15 and 1.43, respectively, for 1982. Because no major vehicle safety design advances occurred during this period, it must be concluded that vehicle occupancies as reflected in the casualty statistics were the same in 1982 as in 1981.

2. An Overall Travel Reduction--It is common practice to assess overall travel changes through fuel sales. Indeed, such an exercise indicates that a 10 percent travel reduction did occur in 1982 (as opposed to 1981 levels) and this closely matches the total accident rate reduction of approximately 12 percent but it does not, by itself, account for the much larger reductions in injuries and fatalities.

3. A Decrease in the Number of Vehicles--During 1982, the number of new passenger car sales certainly suffered a significant downturn but the number of registered vehicles in British Columbia still increased marginally. If anything, the result should have been toward less safety because there evidently were more older cars on the road.

4. A Decrease in the Number of Drivers--Actually, the total number of licensed motor vehicle operators increased by just under 2 percent from 1981 to 1982. In spite of this, however, there was a marked reduction in new licenses issued to young drivers. This will be discussed in more detail later in the paper.

5. Improved Safety Attitudes of Drivers--If something along these lines had occurred, it should be reflected in other statistics such as seat belt wearing rates. In fact, the average surveyed level of seat belt wearing among the general driver population in 1982 was approximately 55 percent for all occupants, which is not considered to be much of an improvement over 1981 when the survey results were, unfortunately, not as reliable. In spite of this, there does seem to be some indication of increased use in the fact that rural fatalities for unrestrained occupants apparently decreased at a higher rate than that for all occupants. Also, accident reports for injury-producing crashes suggest a 5 percent restraint-use increase in 1982 over 1981 for occupants of vehicles involved. This indicates that the various seat belt education and enforcement efforts were at least partially effective.

Figure 3 shows a summary of fatality reductions from 1981 to 1982 for some important accident and victim categories. Because fatalities and fatal accidents showed the greatest overall change, any casual effects should become evident within this subset. Accident categories have been selected so as to highlight the three most important areas of safety at present--age, alcohol use, and seat belt wearing.

In terms of traffic law violations, there is no indication that 1982 was any better than 1981. In fact, for young drivers, who accumulate a substantial

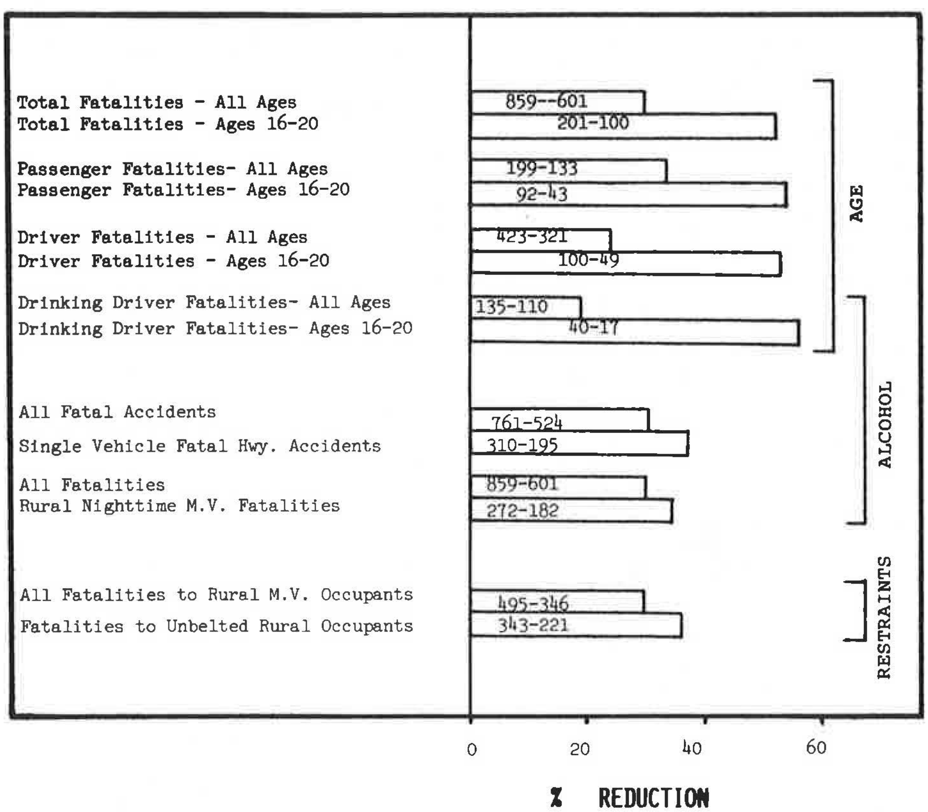


FIGURE 3 Changes in selected fatal accident categories, 1981-1982.

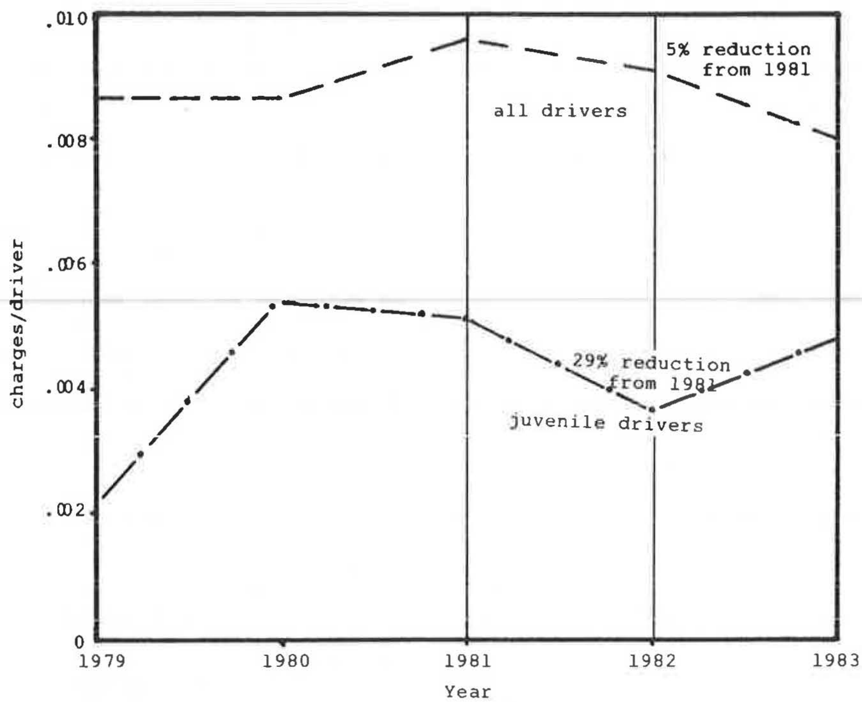


FIGURE 4 DWI charges laid per licensed driver.

number of these convictions, the number of violations per licensed driver rose by 13 percent in 1982. For the major Criminal Code conviction (DWI offenses), Figure 4 shows that there indeed were reductions from 1981 to 1982 but it is doubtful if these could be regarded as significant in light of previous fluctuations.

Alcohol and age are, to a great extent, intertwined, but the fact that two commonly utilized surrogates for alcohol-involved accidents--rural single vehicle and nighttime fatal accidents or fatalities--decreased by more than their respective parent populations, suggests that less drinking-and-driving occurred during 1982. Because alcohol sales (including beer) showed a slight overall increase between 1981 and 1982, the reduction was apparently in driving not drinking. This is supported by the similar levels of decrease for alcohol-involved driver fatalities as for all driver fatalities and by the fact that the proportions of casualty-producing accidents involving alcohol were almost identical for 1982 and 1981 in each age group. The greatest level of over-involvement in alcohol-related fatal accidents has traditionally been with the 16-20 age group and Figure 2 confirms that the most dramatic effects are evident here, specifically among drivers. Figure 5 shows that the reduction in casualty-producing accidents was most pronounced for young drivers at nighttime and that this reduction has continued through 1983. The question still remains, however, as to what could have triggered such apparent changes.

6. The Economy--There is little argument that North America in general and Canada in particular have been in the grips of a severe recession. It has previously been observed that the 1982 casualty reductions were significant and apparently had commenced following the first half of 1981. Various economic indicators that have been published may now be examined to determine whether or not there is any correspondence in timing.

Figure 6 illustrates the major economic changes. It is evident that the beginning of the downturn came close to the middle of 1981 and thus one might be tempted to conclude that the major cause of the reduction was the economy. This can only be confirmed, however, if a fairly reliable economic predictor or predictors can be identified that will reproduce the fluctuations over a number of previous years and then "predict" the 1982 reduction. The most likely candidate for a general trend predictor is the unemployment rate, which Eshler (3) reported following an examination of annual U.S. fatal accident statistics between 1949 and 1973, and which was confirmed by Partyka's work (4) using annual U.S. fatality statistics from 1960 through 1982. It might thus be anticipated that unemployment (or employment) would be a useful indicator, especially if combined with a factor representing travel exposure to help account for the month-to-month variations that Eshler and Partyka did not have to contend with. By grouping the monthly casualty data by gasoline sales and employment, it could be shown (through analysis-of-variance techniques) that both variables significantly differentiated the dependent variable groups ($p < .05$). Gasoline sales are certainly an important aspect of consumer spending but they also relate directly to travel, and therefore accident, exposure and have traditionally shown a seasonal fluctuation. Figure 7 shows how major fluctuations in employment rate alone correspond with major changes in monthly casualties. Least-squares trend lines have been fitted for the periods January 1979 to June 1981 and July 1981 to December 1982.

The question posed by the apparent correspondence between traffic accident casualties and unemployment is, of course, what will happen to traffic safety in the event of an economic recovery? Eshler (3) found that fatal accidents invariably increased following periods of recession and, while the expected recovery has been somewhat delayed, it can be expected that

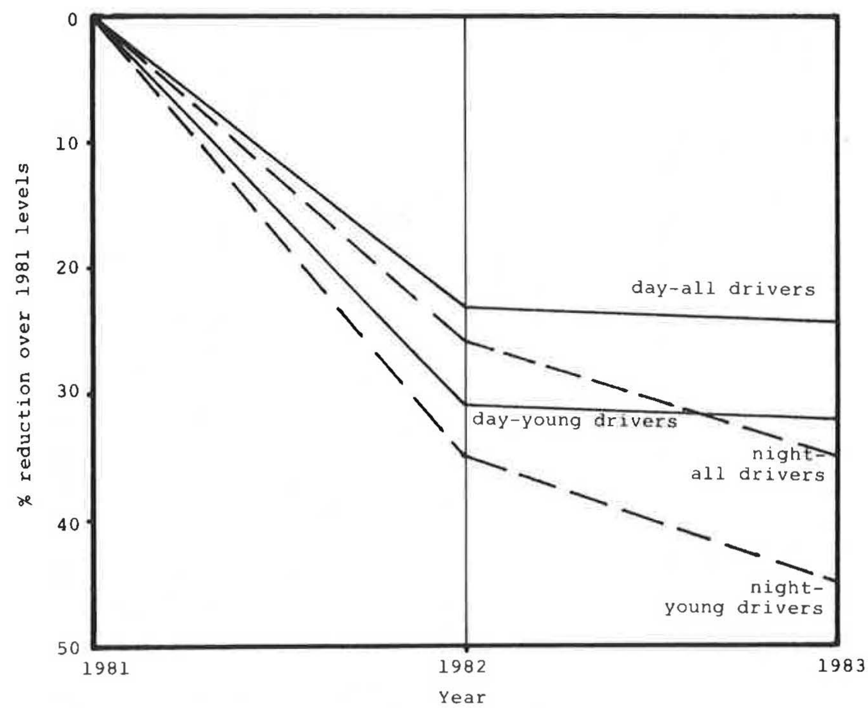


FIGURE 5 Reduction in casualty accident involvement.

the various economic indicators will eventually rise again.

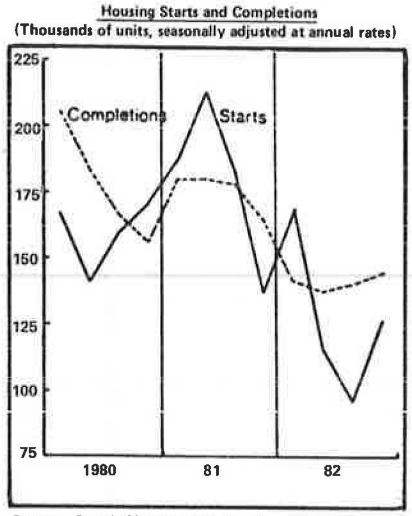
A number of different models were tested using variations of casualty rate and employment statistics combined with gasoline sales and other factors (i.e., reported seat belt use in casualty-producing accidents that were perceived to have changed between 1981 and 1982). In terms of predicting actual casualty numbers, only employment and gasoline sales were found to be useful although seat belt-wearing rates were significantly related to casualties per billion vehicle kilometer (BVK) of estimated travel at a low level ($r^2 = 0.134$). Employment for young males was examined separately from total employment as it was believed that this group would have been hardest hit by the recession. In relation to all casualties, there was no difference between the correlation using total employment and that using young male employment, suggesting that there is a consistent relationship between these two independent variables. In relation to casualties resulting from young driver accidents, however, the use of young male employment in combination with gasoline sales accounted for 80 percent of the variance as opposed to 72 percent of all casualty variance explained when all employment and gasoline sales were used. The best model for total monthly casualties and the actual casualty fluctuations are shown in Figure 8 and there is obviously a reasonable correspondence not only before 1982 but also during that year and 1983 as well. In other words, simply by realizing the trend in employment and fuel sales, one could have predicted the approximate nature and magnitude of the 1982 casualty decrease. The fact that this simple model only accounts for 72 percent of the casualty population variance is not surprising since many other factors are at work. Weather effects for instance, accounted for the peaks in the last quarter of each year and gasoline sales, when considered alone (as a surrogate for travel), produced a corrected r^2 of 0.59.

Fatalities and property-damage-only (PDO) accidents were also found to correlate significantly with economic factors although at a reduced level of association. This was undoubtedly because (a) fatalities in British Columbia are relatively small in number and thus subject to considerable random fluctuation and (b) PDO accidents are not as reliably reported as those where injuries are involved. (PDO accidents are also highly weather related).

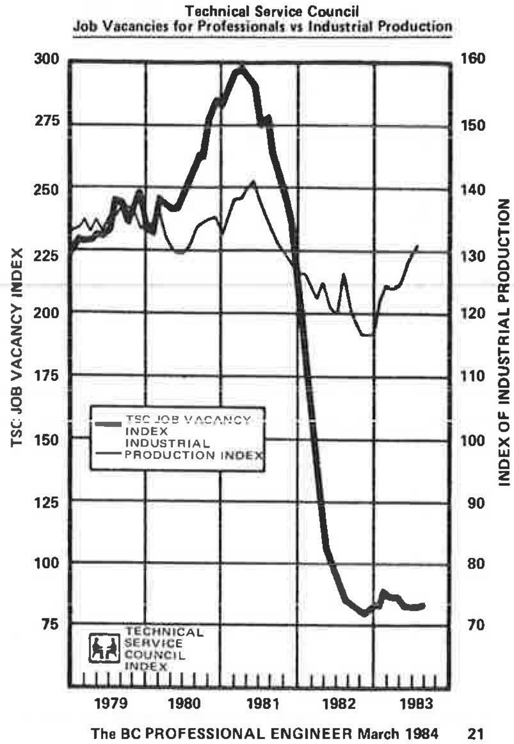
It can thus be confirmed that the major part of the 1982 reduction in the number traffic accident casualties was an expected result of the economic downturn, because a simple economic model could have predicted it without having to consider any non-economic factors. Also, this same model does reasonably well in accounting for the month-to-month and yearly variations before 1982. It should be noted, however, that just because 72 percent of the historical casualty variance can be explained by such means, it cannot be said that the potential exists to reduce casualties by no more than 28 percent no matter what safety efforts are undertaken. The economic factors are superimposed on a general climate of safety consciousness or behavior (and vice versa), which, between 1978 and 1981 in British Columbia, has been considered relatively consistent. It is still theoretically possible to lower this baseline accident level through energetic and judicious application of safety-related regulations and programs.

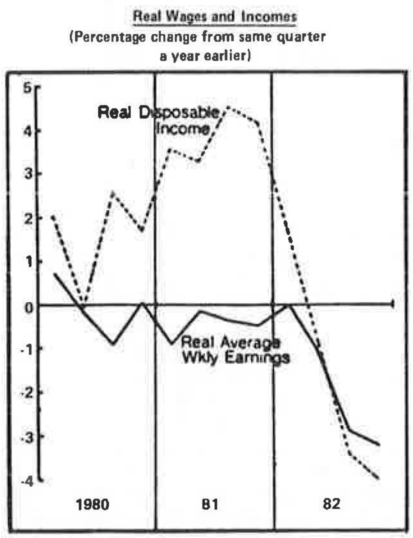
A POSSIBLE MECHANISM FOR CASUALTY REDUCTION IN BRITISH COLUMBIA

As seen earlier, the most noticeable reduction in fatalities during 1981-1982 was for young drivers especially where nighttime driving was involved. This suggests a possible, economically motivated reduction in high-risk driving exposure by young adults. During this period, the number of alcohol-related fatalities and DWI charges for young drivers also fell dramatically although the proportion of alcohol-related casualty accident involvement by age group remained quite stable.



Source: Canada Mortgage and Housing Corporations; The Conference Board of Canada.





Source: Statistics Canada; The Conference Board of Canada.

FIGURE 6 Performance of economic indicators, 1980-1982.

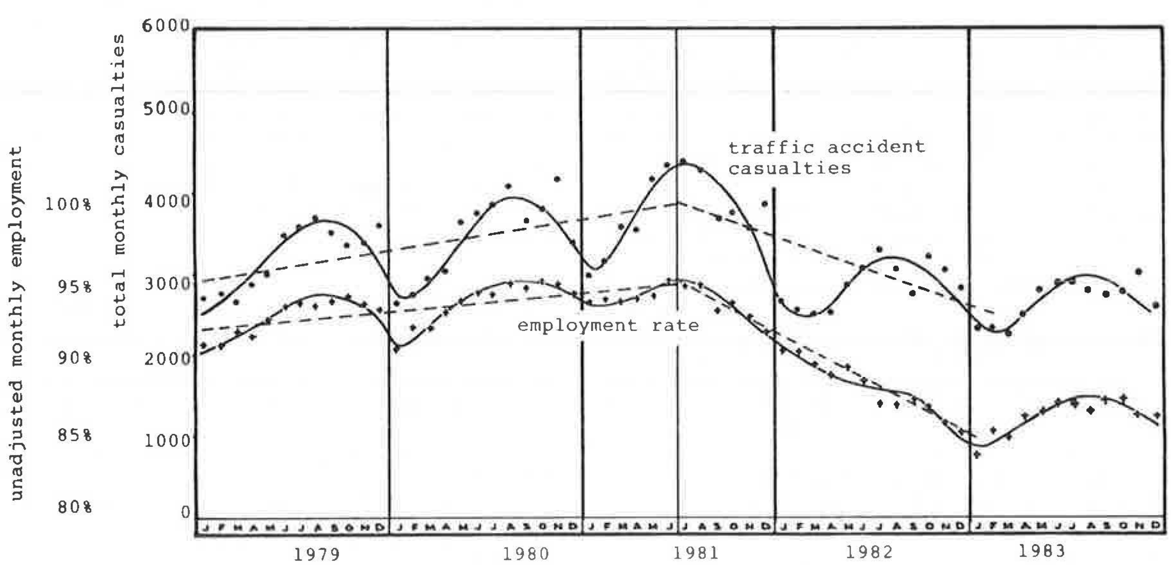


FIGURE 7 The coincidence of employment and traffic casualty trends in British Columbia.

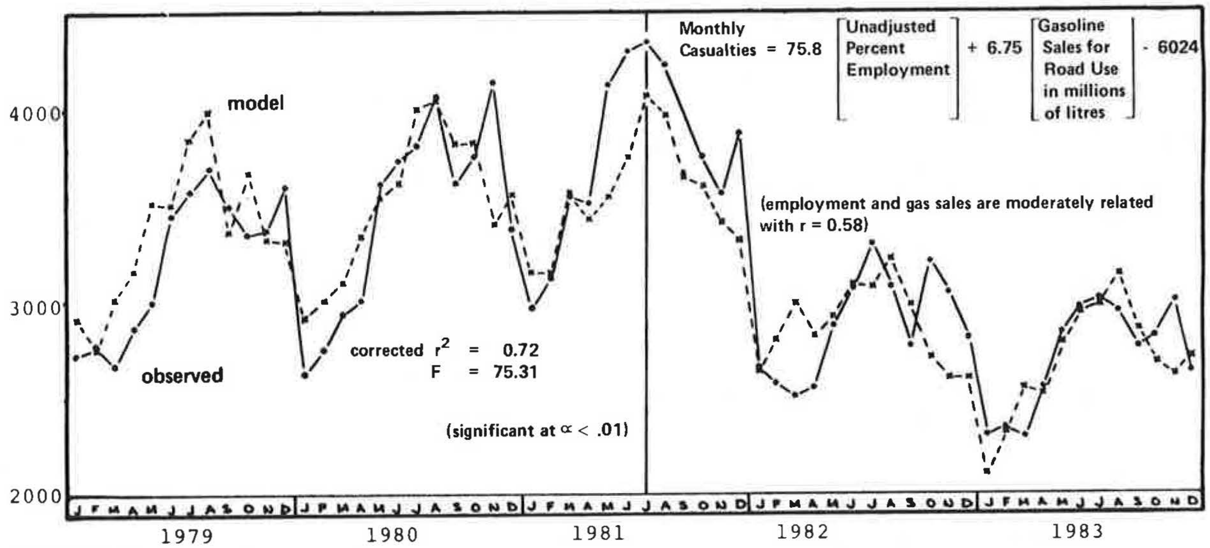


FIGURE 8 Prediction of total monthly traffic casualties in employment and gasoline sales.

Year	Age	Licensed Drivers		16-20 year old New Licenses*		16 year-old Traffic Offenses	
		Male	All	Male	All	Speeding (per lic.)	All (per lic.)
1982	16	9782	15673			2174 (0.139)	3615 (0.231)
	17-19	61396	107112	18650	34458		
	20-24	142308	259551	(-38.5%)	(-36.9%)		
	all	1182641	2079969				
1981	16	12414	19728			2429 (0.123)	4028 (0.204)
	17-19	65691	114354	30340	54634		
	20-24	142219	259228	(+14.0%)	(+14.2%)		
	all	1170963	2044721				
1980	16	10168	15941			2233 (0.140)	3527 (0.221)
	17-19	63372	109511	26607	47827		
	20-24	134739	244985	(+14.0%)	(+12.0%)		
	all	1125485	1950332				
1979	16	9311	14605			2437 (0.167)	3638 (0.249)
	17-19	61875	107117	23335	42720		
	20-24	129258	234317				
	all	1068102	1843203				
1978	16	9349	14548			different reporting procedure	different reporting procedure
	17-19	62099	106631	-	-		
	20-24	127697	229869				
	all	1033538	1769816				

* contains some estimation for ages between 17 and 20 prior to 1981 since the complete age break-down available within this group was only available following the 1980 calendar year.

1982 - expected no. of new licenses = 34588, 61791 (male & total respectively)
1982 - actual no. of new licenses = 18650, 34458
- the difference is significant (X^2) at $p < .001$

licensed drivers 1981-82 increased 1.7% (+ 0.9% for males)
but new licenses issued 1981-82
to 16-20 year-old drivers decreased 36.9% (-38.5% for males)

FIGURE 9 Changes in new licenses and traffic violations.

There are two possible explanations for reduced travel or exposure: less driving by licensed drivers or fewer licensed drivers. The latter possibility can be readily tested by examining the driver license records from 1978 to 1982 and estimating from these the historical trend in new licenses issued annually to young (16-20 year-old) drivers. Although from 1978 to 1981 the number of new licenses rose by approximately 14 percent per year as shown in Figure 9, it dropped by 37 percent in 1982. The combination of both factors can be investigated by testing the hypothesis that reduced travel was the sole cause of all the casualty accident reductions, using an inferential type of approach to the data analysis. Begin by assuming that between 1981 and 1982, there was no driver attitude toward behavioral changes, that is, the relative risk of accident involvement given a certain level of exposure for each age group did not change from 1981 to 1982. This is akin to saying that 100 percent of the accident reduction resulted from changes in driving exposure. Based on fuel sales in British Columbia (5) and fuel surveys from Statistics Canada (6), it can be estimated that travel was approximately 26.8 and 24.0 BVK in 1981 and 1982, respectively, which represents a 10 percent reduction. For 1983, the estimate was 22.8 BVK, which represents a 5 percent reduction from 1982. Using the estimated 24-hr driving exposure in kilometers of travel based on the 1979 National Driving Survey results for British Columbia (7), and casualty accident proportions by age (taken from unpublished data on the "Counterattack" program, which was supplied by the British Columbia Ministry of the Attorney General), statistics for 1981 are given in Table 1.

TABLE 1 Casualty Accident Proportions by Age for 1981

Age Group	Likely Driving Exposure (BVK)	Drivers Involved in Casualty-Producing Accidents		Total Casualty Accident Involvement per BVK
		Total	Percentage	
16-20	10.0% x 26.8 = 2.68	11,987	25.3	4,473
21-25	10.6% x 26.8 = 2.84	9,308	19.6	3,278
26-45	42.7% x 26.8 = 11.44	17,357	36.6	1,517
46-65	30.3% x 26.8 = 8.12	6,720	14.2	828
66+	6.4% x 26.8 = 1.72	2,016	4.3	1,172
Total		47,388	100.0	11,268

TABLE 2 Casualty Accident Proportions by Age for 1982

Age Group	Drivers Involved in Casualty-Producing Accidents		Casualty Accident Involvements per BVK (from 1981)	Estimated Driving Exposure (BVK)
	Total	Percentage		
16-20	8,155	22.1	4,473	1.82
21-25	7,252	19.6	3,278	2.21
26-45	14,253	38.6	1,517	9.40
46-65	5,526	15.0	828	6.67
66+	1,746	4.7	1,172	1.49
Total	36,932	100.0	11,268	21.59

Using the 1981 ratio of casualty accident proportion to exposure, it is possible to (a) combine this with the 1982 casualty accident proportion and then to (b) work backwards to obtain what would have been the exposure percentages had no change in the ratio of casualty accident involvements per BVK of travel occurred. These statistics are given in Table 2. It is known, however, that total travel in 1982 was approximately 24 BVK--not the 21.6 BVK arrived at previously. The only solution to the discrepancy is to postulate a decrease in the driving risk, that is, a reduction in the casualty accident involvements per BVK. The mechanism for applying such a driving risk reduction across the various age groups is not known but it can be assumed that the range of eventualities will be covered by the following cases:

i. Distributing the decrease in risk in proportion to the size of the 1981 risk levels (accidents per BVK), which amounts to an equal distribution of percentage risk reduction across all age groups; or

ii. Distributing the decrease in risk in proportion to the level of casualty accident reduction between 1981 and 1982 in each age group. This amounts to a differential percent risk decrease by age group with the effect assumed greatest for those age groups having the highest levels of accident reduction.

For Case i it is found that approximately a 10 percent risk reduction applied equally to all age groups will result in bringing the total travel value up to the correct level, as given in Table 3.

TABLE 3 Total Travel Value

Age Group	1981 Casualty Accident Involvement per BVK	1982 Adjusted Casualty Accident Involvement per BVK	1982 Revised Estimated Driving Exposure (BVK)
16-20	4,473	4,024	2.03
21-25	3,278	2,949	2.45
26-45	1,517	1,365	10.44
46-65	828	745	7.42
66+	1,172	1,054	1.66
Total	11,268	10,137	24.00

TABLE 4 Risk Reduction Adjustments

Age Group	1981 Casualty Accident Involvement per BVK	1982 Adjusted Casualty Accident Involvement per BVK	1982 Revised Estimated Driving Exposure (BVK)
16-20	4,473	3,713	2.20
21-25	3,278	2,883	2.52
26-45	1,517	1,378	10.34
46-65	828	753	7.34
66+	1,172	1,090	1.60
Total	11,268	9,817	24.00

TABLE 5 Comparison of Travel Changes with Reduction in Accidents Based on Travel Decrease Alone

Age Group	1981 Casualty Accident Involvement per BVK	Apparent Change in Travel from 1981 to 1982 (BVK)		Reduction in Accidents Based on Travel Decrease Alone (BVK)	
		Case i	Case ii	Case i	Case ii
16-20	4,473	0.65	0.48	2,908	2,147
21-25	3,278	0.39	0.32	1,278	1,049
26-45	1,517	1.00	1.11	1,517	1,684
46-65	828	0.70	0.78	580	646
66+	1,172	0.06	0.12	70	141
Total	11,268	2.80	2.81	6,353	5,667

Similarly, when the level of risk reduction is adjusted to reflect the percentage of the 1981-1982 casualty accident decrease in each age category as compared to the overall percentage decrease, the result would be that the proposed risk reduction would range from a high of approximately 17 percent for 16 to 20 year-olds down to approximately 7 percent for those age 66 and older. The results of applying these decreases are given in Table 4.

To assess the degree to which reductions in driving exposure have influenced the change in accident occurrence, as opposed to any postulated changes in risk-taking behavior, the 1981 risk levels can be applied to the apparent travel changes (in BVK) and the results compared to the actual change that occurred, as given in Table 5.

Because the total recorded reduction of casualty accident involvement for drivers was 10,456 (47,388-36,932), it is apparent that an overall reduction in travel alone can account for, at most, 61 percent (Case i) and perhaps only 54 percent (Case ii). The regression model mentioned earlier showed that 59 percent of the monthly casualty variance could be explained by gasoline sales (travel) alone.

It should be noted here that even though a net travel reduction can account for, at most, 61 percent of the observed accident reduction, a substantial portion of the postulated decrease in risk of accident involvement could come about through a switch from nighttime to daytime driving. Figure 5 lends support to the possibility that nighttime driving may have decreased considerably more than daytime driving and, because the former is associated more with nonessential social activities, it is logical to assume that the economic recession would initially affect it the most although as job-hunting activity decreases, it might be expected that the difference would become less significant.

The expected reduction, based solely on a consideration of net travel decrease, thus only accounts for at most, 61 percent of the actual change. (Within this 61 percent, it can be further estimated that approximately 7 percent is due to the fewer number of licensed young drivers as mentioned earlier.)

In other words, reduced travel cannot have been the only factor. Even seat belt usage would only add, at most, 2 percent to the reduction explained, and thus, a significant percentage is left that must somehow be related to other changes in driving behavior.

In summary, it may be unreasonable to suggest that, of the significant casualty accident decreases that occurred between 1981 and 1982, a maximum of approximately 63 percent could possibly be explained by an economically motivated reduction in travel (especially among young drivers during night hours) and the small increase in restraint use. The remaining 37 percent or so is as yet unexplained and could be associated with a change in driver risk-taking behavior. It should be noted, however, that even such postulated behavioral changes as these could be linked to the depressed economic situation and would thus be reversible in the event of an eventual improvement.

CONCLUSIONS

The major conclusions arising out of this investigation are as follows:

1. The 1982 reduction in traffic accident casualties in British Columbia was a real and significant event that cannot be attributed to chance alone.

2. The major part of this reduction can be attributed to the effects of the economic recession. Reduced travel was undoubtedly a significant factor, but there still remains a significant portion that cannot as yet be explained in such simple terms and that will require further research to uncover.

3. When the province recovers from the recession, there is every indication that traffic accident casualties will rise again; although the exact speed and extent of the rise are at present uncertain, the casualties should follow the general trend in employment levels.

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Using Accident Records To Prioritize Roadside Obstacle Improvements in New Mexico

JAMES D. BROGAN and JEROME W. HALL

ABSTRACT

This paper contains a description of a process for identifying sections of rural New Mexico Interstate, primary, and secondary highways with significant fixed-object accident experience. Data bases for the analysis are the computerized accident record and roadway inventory systems for the 3-fiscal-year period from 1980 to 1982. The rate quality control method is used as the statistical technique to identify those sections of roadway that are most in need of examination. Accident and inventory information are combined to calculate critical accident rates for sections of roadway on each of the three systems. Calculated critical rates are then compared with the actual rates on each section, and a listing of sections arranged by criticality (the difference between the actual and critical rates) is obtained. This listing is used by New Mexico State Highway Department personnel to prioritize locations for implementing safety improvements. The procedure is applicable to the analysis of other subsets of accidents as well. Data quality is critical for the proper application of the technique; factors other than accident experience, in addition, must be considered in the cost-effective development of accident reduction countermeasures.

National statistics (1) indicate that over 63 percent of fatal traffic accidents involve only a single vehicle. Even when pedestrian and pedalcycle accidents are excluded, single-vehicle accidents still account for over one-half of all traffic fatalities. The most frequently cited "first harmful event" for single-vehicle fatal accidents on a national level is collision with a fixed object (48 percent of all single-vehicle fatalities), followed by collisions with pedestrians and pedalcyclists (29 percent) and overturning accidents (17 percent). Rural highways, which account for 44 percent of the nationwide total vehicle miles of travel (VMT), account for 56 percent of the single-vehicle fatal accidents. Despite the emphasis on clear roadsides for Interstate highways, occupant fatalities in single-vehicle accidents remain the largest component of the fatality toll on these facilities.

Traffic accident data in New Mexico reflect many of the national trends. In 1983, for example, 69 percent of New Mexico's fatal accidents were of the single-vehicle type, while for the 3-fiscal-year period from 1980 to 1982, over 58 percent of the nonpedestrian fatal accidents involved a single vehicle (2). Because of the rural nature of New Mexico, 70 percent of fatal accidents occurred in rural areas, even though less than 60 percent of the state's VMT take place in these areas.

Other New Mexico Traffic accident characteristics deviate from national norms. New Mexico's fatal accident rate is consistently one of the highest in the nation, while the percent of fatal accidents involving multiple vehicles is among the lowest. Fatal overturning accidents, for example, are overrepresented, probably because of the relatively uncluttered roadside terrain in many parts of the state (3). On the other hand, fixed-object accidents occur somewhat less frequently than expected. The sum of these two accident classes could generally be described as run-off-the-road accidents. Fixed-object accidents in 1982 accounted for 14 percent of the state's total accidents and 12 percent of its fatalities. Because of the relative ease with which fixed-object countermeasures may be implemented, a study was undertaken in New Mexico to establish a manageable set of hazardous locations and to develop improvement priorities.

The purpose of this paper is to report on a procedure for ranking in priority order rural fixed-object accident site improvements in New Mexico. Although the general aspects of the procedure are not unique (4), certain features of its application are examined in greater detail. The computerized accident record and roadway inventory systems are combined to identify roadway sections with critical fixed-object accident rates. Computerized data are supplemented by the use of hard-copy accident reports, photologs, and individual site visits. Although rural Interstate segments were initially examined from the records system, principal emphasis for improvements is given to rural federal-aid primary (FAP) and federal-aid secondary (FAS) facilities in the state. Fixed-object accidents involving guardrails, moreover, are not considered because they were the subject of a previous study (5).

Subsequent sections of this paper contain descriptions of fixed-object accident experience in the state, discussions on the application of the rate quality control procedure for identifying critical fixed-object accident locations, and an outline of other considerations in the ranking in priority order of improvement sites. While the specific examples developed in this paper apply to rural, single-vehicle accidents in New Mexico, the general principles are applicable to other significant subsets of traffic accidents.

FIXED-OBJECT ACCIDENT CHARACTERISTICS

Computerized accident records show that during the 3-fiscal-year period from 1980 to 1982, approximately 143,000 accidents were reported in New Mexico. Other accidents, particularly those involving a single vehicle, no doubt occurred but are not in the record system for several reasons (6). These reported accidents were distributed by accident class as indicated in Table 1. The data show that fixed-object accidents are an important, although not major, portion of New Mexico's accident experience.

TABLE 1 Accidents by Class for Fiscal Years 1980-1982

	Total Accidents		Fatal Accidents	
Accident Class	No.	Percentage	No.	Percentage
Other vehicle	87,773	61.3	450	30.2
Fixed object	20,014	14.0	181	12.1
Overturning	11,526	8.1	492	33.0
Pedestrian/pedalcyclist	3,073	2.1	297	19.9
Other	20,776	14.5	72	4.8
Total	143,162	100.0	1,492	100.0

TABLE 2 Single-Vehicle, Fixed-Object Accidents by Location and Severity

Location	Fatal	Injury	PDO	Total	Severity Index
Rural	108	2,164	4,200	6,472	0.35
Urban	71	3,279	9,877	13,227	0.25
Total	179	5,443	14,077	19,699	0.28

Note: Severity index = (fatal + injury)/total.

Further analysis found that the 20,014 fixed-object accidents shown in Table 1 include 315 accidents involving two or more vehicles. The remaining 19,699 single-vehicle, fixed-object (SVFO) accidents are distributed by location and severity as shown in Table 2. Although two-thirds of the SVFO accidents occur in urban areas, over 60 percent of the fatal crashes and almost 40 percent of the injury accidents are in rural locations. The severity index (the ratio of fatal plus injury accidents to total accidents) is thus considerably higher for rural areas undoubtedly because of higher speeds, different types of fixed objects, and the probable underreporting of some rural, single-vehicle, property-damage-only (PDO) accidents.

The 6,472 rural SVFO accidents include many that occurred on nonfederal-aid roads, such as other state, county, Indian reservation, and U.S. Forest Service roads. The exclusion of accidents on these other roads as well as fixed-object accidents involving guardrails (6) provided a sample of 3,432 nonguardrail SVFO accidents on New Mexico Interstate, FAP, and FAS systems during the 3-year period. It is this set of accidents (approximately 2 percent of New Mexico's total accident experience) that is examined in greater detail in this paper.

Figure 1 shows the process used to select the accidents of interest, beginning with a computer tape of all New Mexico traffic accidents for the 3-year period and ending with a set of 3,432 nonguardrail SVFO accidents on rural federal-aid highways. Although the average severity index (0.38) for these accidents on the Interstate system is identical to those for the FAP and FAS systems, the systems clearly differ in their roadway and roadside design characteristics. Previous research has documented substantial variation in severity indices as a function of the type of object struck (3). An alternate technique for assessing the severity of impact with a particular object type is to weight the average NHTSA costs for fatal, injury, and PDO accidents by the probability of these severity levels. The probabilities can be estimated by the observed relative proportions of impacts with a specific object type that result in a fatal, injury, or PDO accident. Because of the subjective aspects of the NHTSA costs and the lack of homogeneity of objects within a particular category, the results of this analysis are relative rather than absolute. The average cost for all accidents examined in this project was $8,800. The severity indices and estimated costs of crashes involving various object types are given in Table 3.

The absence of trees and utility poles along New Mexico's rural Interstate is reflected by the proportions of crashes involving these fixed objects. Culverts, medians, and traffic signs, on the other hand, comprise a larger percentage of Interstate than FAP and FAS crashes. Fences (right-of-way fences on the Interstate) and embankments (in reality, consisting of both cut and fill slopes) are struck with similar frequencies on both systems. The category "other" includes barricades and construction material and equipment; these fixed-object types constitute a slightly larger portion of the accident experience on the Interstate system.

The average cost values exhibit substantially more variation than the severity indices. To a certain extent, this cost analysis procedure emphasizes those objects that are more likely to result in a fatality. However, caution must be exercised in using small accident samples where one or two fatalities can dramatically alter the average costs.

Other characteristics of rural SVFO accidents are summarized in Table 4. In general, these accidents occur on curves more often than on tangent sections and are more common on downgrades and during hours

TABLE 3 Fixed-Object Accident Type by Road System for New Mexico for Fiscal Years 1980-1982

	Interstate			FAP and FAS		
Fixed Object Type	Percentage	Severity Index	Cost ($)	Percentage	Severity Index	Cost ($)
Culvert	15	0.47	13,800	8	0.48	8,700
Embankment	16	0.41	12,600	18	0.47	10,300
Bridge	4	0.39	4,600	2	0.45	14,100
Tree	2	0.50	19,800	12	0.44	15,900
Utility pole	1	0.45	5,400	5	0.40	9,400
Ditch	6	0.30	8,700	11	0.37	8,400
Median or curb	6	0.48	10,700	1	0.24	3,000
Guard posts	4	0.18	2,400	2	0.27	3,400
Fence	21	0.32	6,300	23	0.32	3,900
Traffic sign	7	0.15	11,400	4	0.38	7,800
Other	18	0.43	14,900	14	0.37	7,100

Note: Severity index (SI) = (fatal + injury)/total; FAP and FAS = federal-aid primary and secondary, respectively.

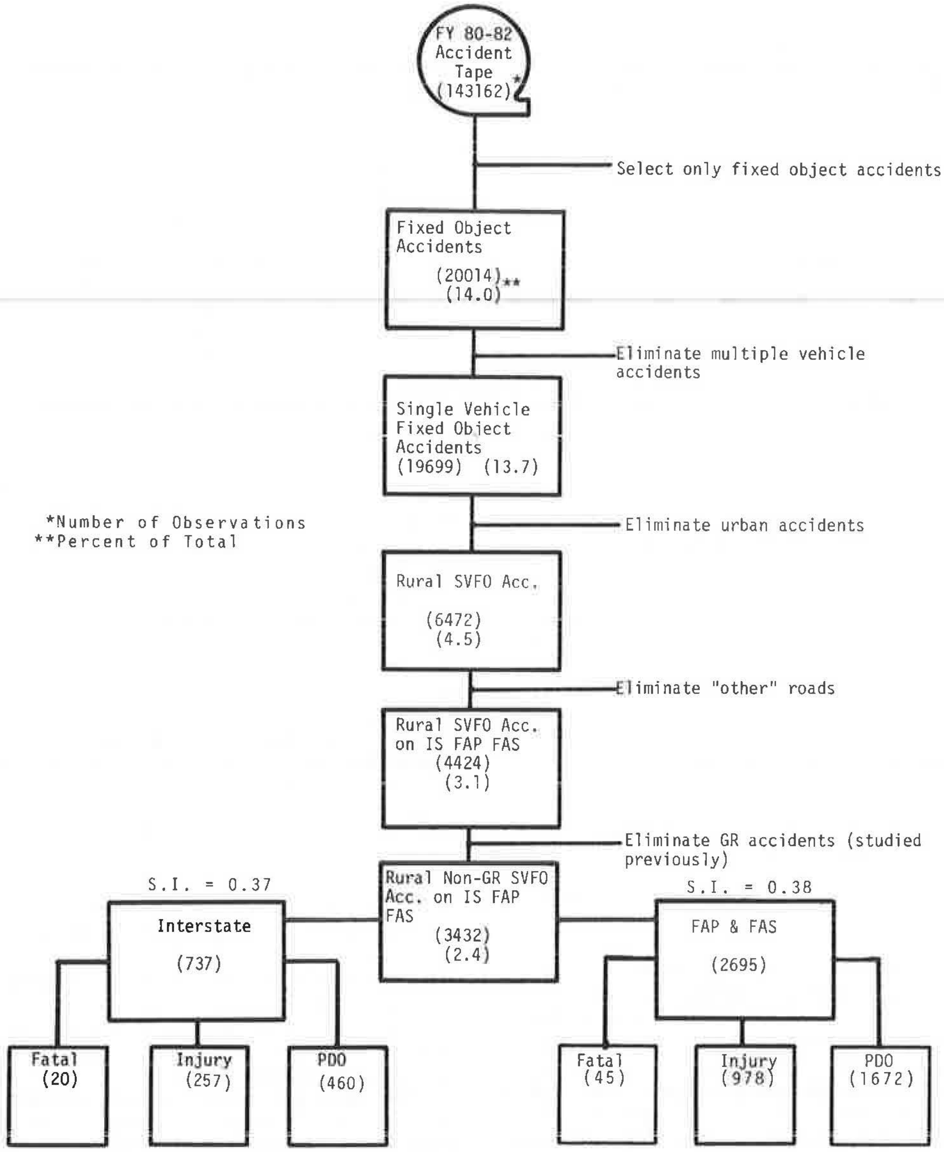

FIGURE 1 Accident selection procedure.

TABLE 4 Characteristics of Rural, Nonguardrail SVFO Accidents for New Mexico for Fiscal Years 1980-1982

	Interstate (%)	FAP and FAS (%)
Weather		
Clear	84	84
Rainy	16	16
Horizontal alignment		
Straight	88	65
Curve	12	35
Vertical alignment		
Level	76	66
Grade	24	34
Lighting		
Day	51	40
Night	49	60

of darkness. The results are consistent with those reported in the technical literature and the findings of previous studies of run-off-the-road accidents in New Mexico (3,5).

IDENTIFICATION OF CRITICAL LOCATIONS

Discussion in the previous section centered on the characteristics of nonguardrail, single-vehicle fixed-object accidents on New Mexico's rural Interstate, primary, and secondary roadway systems. Although this information is perhaps interesting from an aggregate statistical standpoint, it is of little use in identifying hazardous locations since specific objects on moderate volume rural highways are rarely struck more than once and, because exposure, in terms of volumes and section lengths, is not specifically taken into account.

The technical literature (7) discusses a number of techniques for the identification of hazardous locations. According to one survey (8), the most commonly used procedure is based on the number of accidents, followed by techniques using accident rates and crash severity. The shortcomings of relying primarily on the number of accidents are well documented. Although rate-based techniques incorporate exposure, thus eliminating one problem, they induce artificially high rates when only a few accidents are combined with low exposure. If reasonably complete and reliable data are available, this deficiency in the identification of hazardous locations may be overcome through the use of quality-control, statistical techniques, commonly known as rate quality control methods (4,9). Approximately 15 states make some use of this technique in the process of identifying hazardous locations (10).

Subsequent sections of this paper contain discussions on the application of the rate quality control method to the identification of rural, fixed-object accident locations in need of remedial action. The technique itself is discussed first; application of the technique to rural federal-aid highways in New Mexico is then considered.

THE RATE QUALITY CONTROL METHOD

The rate quality control method calculates a critical accident rate (RC) for each section of roadway. The value of RC is a function of the systemwide accident rate (RA), the amount of VMT on the section (m), and a factor (k) based on the desired level of statistical significance. The relationship is

$$RC = RA + \{k[(RA/m)^{1/2}]\} + 0.5/m \quad (1)$$

The term RA/m is an estimate of the variance of the accident rates, while 0.5/m is a continuity correction. Agencies using this technique for the general identification of hazardous locations reportedly use a variety of levels of significance (α) ranging from 0.005 to 0.05, and possibly higher. The choice of α establishes the value k in the equation, with lower values of α corresponding to higher values of k and resulting in a shorter list of hazardous locations. Higher values of α reduce the likelihood that a truly hazardous location will be overlooked, but the larger list of locations generated in this process will include many sites that are not actually hazardous. Under conditions of financial and personnel constraints, it may be appropriate to select a value of α that will result in a manageable list of locations warranting further study. Using a normal distribution table, the choice of α = 0.05 yields a value for k of 1.645, and Equation 1 reduces to

$$RC = RA + \{1.645[(RA/m)^{1/2}]\} + 0.5\ m \quad (2)$$

where

RC = section rural nonguardrail, fixed-object critical accident rate (accidents per million VMT on the section),
RA = systemwide rural nonguardrail, fixed-object accident rate (total SVFO accidents per total travel, not the average of individual section rates), and
m = million VMT on the section.

The critical rate is obviously greater than the systemwide accident rate. It decreases with increasing travel on the individual study sections. If the amount of travel and the SVFO accident experience on a section are known, the actual section rate can be calculated and compared with its critical rate. Within the limitations imposed by the quality of the traffic accident and travel data, sections where the actual rate exceeds the calculated critical rate are said to be hazardous at the 5 percent level of significance.

APPLICATION OF THE RATE QUALITY CONTROL TECHNIQUE

Application of the foregoing technique for establishing roadside obstacle improvement priorities in New Mexico involves identifying sections of rural Interstate, primary, and secondary highways with higher-than-critical, fixed-object accident experience. The initial step involves combining the computerized accident record and roadway inventory data files to determine the RA for each of the three roadway systems. The next step involves using these data files to calculate and compare the actual and critical rates on each roadway section. Sections are then ranked according to their criticality, that is, the difference between the actual section rate and the critical rate for that section. The process is shown in Figure 2 and is described in the following paragraph.

The critical, fixed-object accident rate calculation begins by selecting from the accident file those accidents of interest, in this case, rural single-vehicle, nonguardrail, fixed-object accidents on the Interstate, primary, and secondary systems. The total travel by system for the 3-year study period is estimated by using the individual section lengths and annual average daily traffic counts (ADTs) in the inventory file. The average rates are then calculated for each system.

There are a number of techniques for establishing individual roadway sections. Ideally, sections should be homogeneous with respect to roadway design and development, traffic volume, and speed. While short section (<0.5 mi) are more likely to be homogeneous, they also have limited accident experience. The New Mexico roadway inventory establishes sections principally on the basis of the construction contracts under which they were built. Thus, the sections vary in length, but are reasonably consistent in design and operational features. The inventory contains 305, 1,237, and 1,028 sections on the rural Interstate, primary, and secondary systems, respectively. Inventory sections average 3 mi in length, but there is considerable variation among individual sections. To facilitate the analysis and reduce the number of individual roadway sections to be considered, the traffic volumes of adjacent sections were compared. If ADTs on adjacent sections differed by less than 100 vehicles per day (vpd), the sections were combined. This process reduced the total number of study sections from 2,570 to 967.

Determination of critical accident rates on these sections is accomplished by first calculating the VMT on each section (the product of ADT, section length, and the 1,096 days in the 3-year period). A critical accident rate is then calculated using VMT and the previously calculated accident rate for the roadway system. Those sections on which the actual rate exceeds the critical rate are flagged and ranked according to the difference between the two rates.

PROGRAM RESULTS

Calculated systemwide SVFO accident rates for the Interstate, primary, and secondary systems are 0.114, 0.187, and 0.344 accidents per million VMT, respectively. As expected, the Interstate rate is relatively low (one fixed-object accident for each 8.8 million VMT) while the secondary rate is three times higher (one fixed-object accident for each 2.9 million VMT). Use of these systemwide rates results in the following critical rate calculations at the 5 percent level of significance for individual sections on each of the three systems:

$$RC = 0.114 + \{0.555[(1/m)^{1/2}]\} + 0.5/m\ (IS) \quad (3)$$

$$RC = 0.187 + \{0.711[(1/m)^{1/2}]\} + 0.5/m\ (PR) \quad (4)$$

$$RC = 0.344 + \{0.965[(1/m)^{1/2}]\} + 0.5/m\ (SE) \quad (5)$$

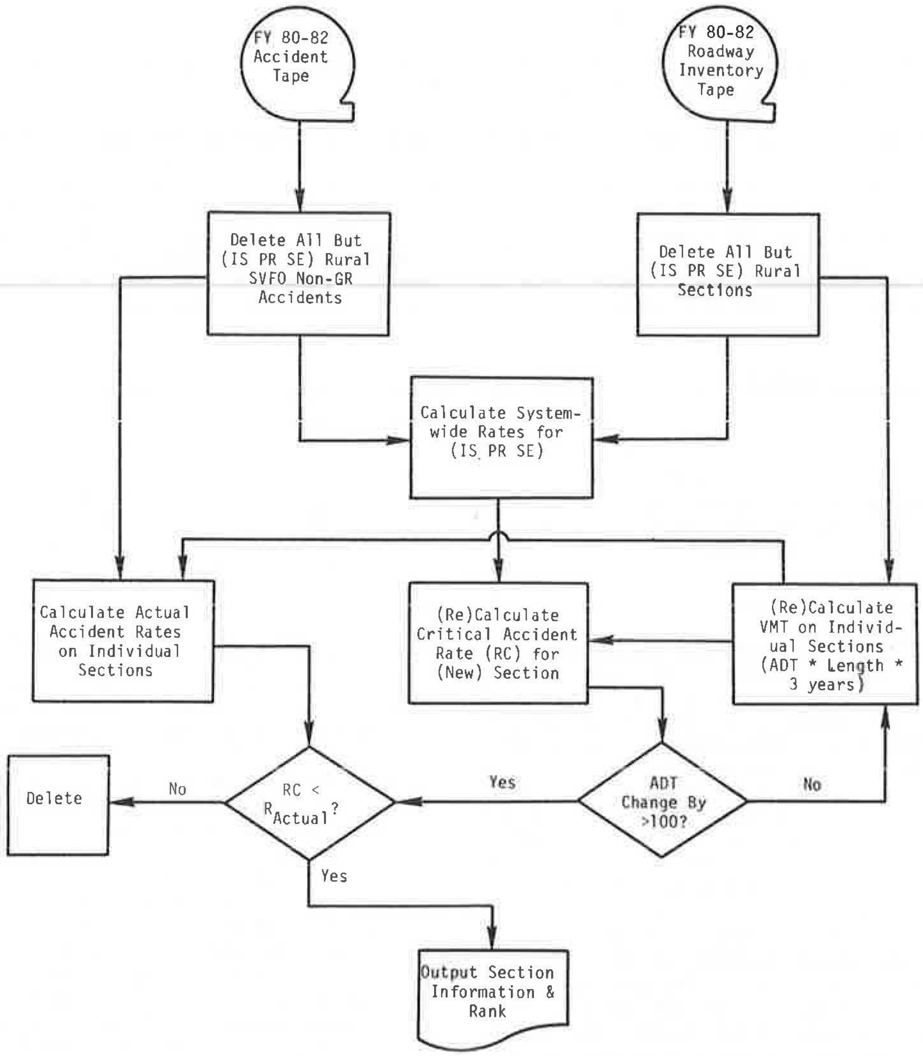

FIGURE 2 Calculation of critical fixed-object accident rates for New Mexico for fiscal years 1980-1982.

where IS is Interstate system, PR is primary system, and SE is secondary system.

For the purposes of this analysis, the value of m is the number of million VMT on a section during the 3-year study period. The critical rate relationships given in the preceding equations are plotted by roadway system in Figures 3, 4, and 5. Observed accident rates above the plot are critical at a level of significance of $\alpha = 0.05$. The abscissa of each figure is actually the ADT on a section exactly 1 mi long. It may also be interpreted as the daily VMT on a section with a length other than 1 mi. For example, to apply Figure 4 to a 3-mi roadway section with an ADT of 5,000, the figure is entered at 15,000 on the abscissa. Although the principles underlying the development of these figures have general applicability, the actual figures are only valid for the 3-year study period on rural New Mexico highways.

The application of this procedure identified a total of 14 Interstate, 47 primary, and 59 secondary sections that had actual accident rates higher than the critical rates. In other words, between 10 and 14 percent of the sections on these routes were judged to be hazardous. An example of the output information showing the five most critical sections on the FAS system is shown in Table 5.

The information listed in Table 5 shows the administrative route number on which the section is located, the beginning and ending mileposts of the critical section, the number of SVFO accidents on

TABLE 5 Fixed-Object Accidents on Rural New Mexico Secondary Roads

Administrative Route No.	Beginning Milepost	Ending Milepost	No. of Accidents	Daily VMT	Rate per Million VMT Actual	Rate per Million VMT Critical
1303	0.0	10.6	13	531.0	22.36	2.47
1120	0.0	1.5	4	274.5	13.31	3.77
1362	0.0	0.4	6	699.5	7.83	2.10
1226	12.9	14.4	3	362.9	7.55	3.13
1316	8.1	9.0	2	238.4	7.66	4.15

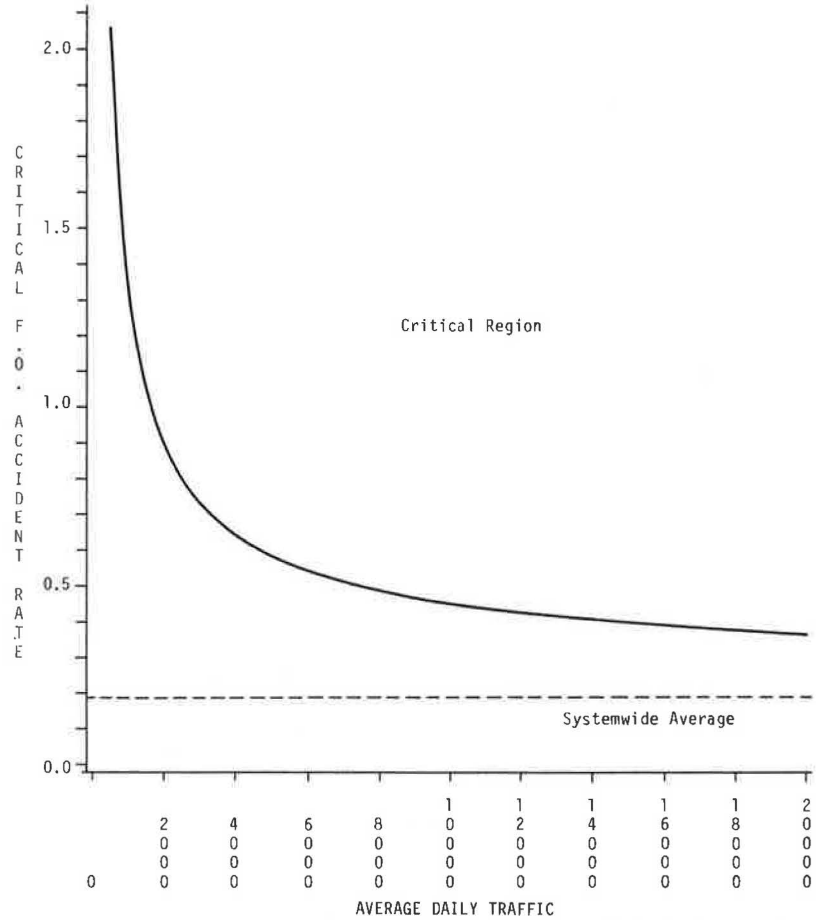

FIGURE 3 Critical fixed-object accident rates for rural New Mexico Interstates for fiscal years 1980-1982.

the section during a 3-year period, the daily VMT on the section, and the actual and critical accident rates on the section. The sections are ranked by criticality, that is, the difference between the actual and critical accident rates for the section. Although it is not obvious from the abbreviated listing in Table 5, a slightly different ranking is obtained if the sections are arranged in decreasing order by the ratio of actual to critical accident rates.

Listings such as that shown in Table 5 can be used by New Mexico State Highway Department engineers for establishing priorities for those sections of various roadway systems in the state that appear to warrant more attention in the amelioration of fixed-object accident hazards. To be useful, however, the list must be restricted to a manageable number of sections that can be examined in greater detail. The 120 highway sections identified by this process were judged to be too many to be accommodated within the constraints of this program. One logical approach for shortening the list is to use a smaller value of α. This has the effect of increasing the value of k in the critical rate equation, thus increasing the value of RC and reducing the number of critical sections. A principal shortcoming of this approach is that 20 percent of the sections, including several short sections near the top of the list, had only 2 or 3 accidents during the 3-year period. Although these sections may truly be critical, it is also quite possible that the miscoding of a single accident's location by as little as 0.1 mi could alter the section's classification from hazardous to safe. A preliminary attempt to restrict the number of study sections involved the use of cutoff values, expressed as number of accidents per mile (1.2 for the FAP, 1.7 for the FAS). Although this effort eliminated a few short sections with low travel and 2 or 3 accidents, its principal effect was to eliminate longer sections. A separate analysis of construction and project planning records also revealed that several sections had recently been reconstructed, and these sections were dropped from further analysis.

OTHER CONSIDERATIONS

Although the use of computerized accident record and roadway inventory data files provides an excellent guide for identifying roadway sections with high fixed-object accident experience, in reality, several additional steps are necessary before accident countermeasures may be implemented. Because it is often difficult to determine with certainty from computerized records whether the same objects are being struck repeatedly, the next logical step in the process must be a review of hard-copy accident reports for roadway sections of interest. This process uncovered a number of instances in which the accident locations were miscoded. Because roadside improvements are typically made at spot locations rather than overextended sections, a more thorough review of identified sections is necessary before countermeasures may be implemented. As a first step in this process, photolog reviews of the critical sections were undertaken to identify specific objects along the roadside that may warrant attention. This effort

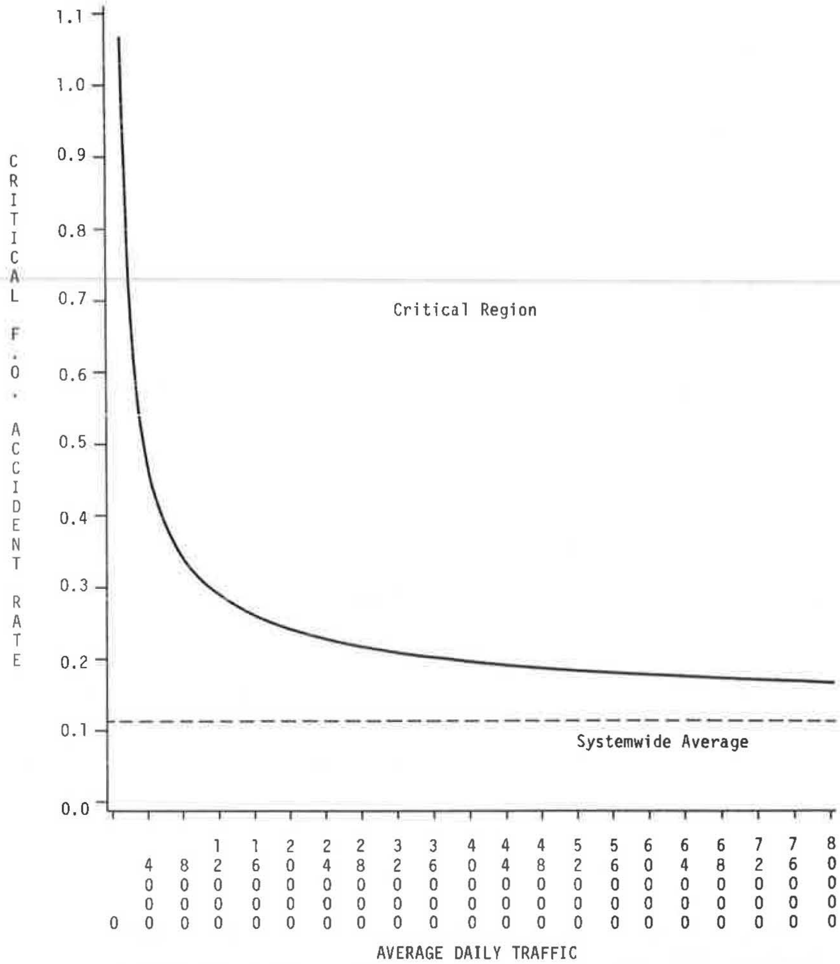

FIGURE 4 Critical fixed-object accident rates for rural New Mexico primary systems for fiscal years 1980-1982.

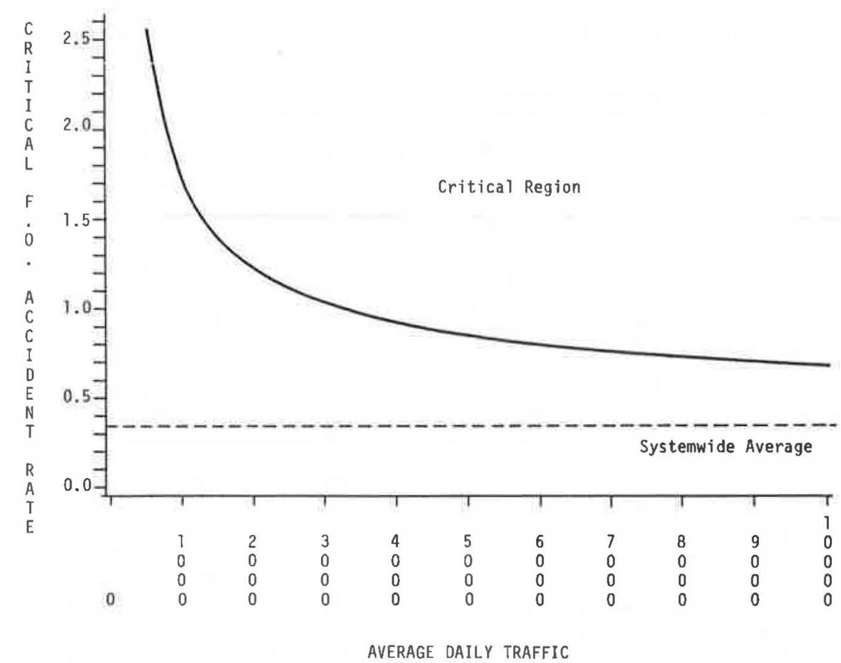

FIGURE 5 Critical fixed-object accident rates for rural New Mexico secondary systems for fiscal years 1980-1982.

was quite helpful, although certain types of roadside fixed-objects (ditches, culverts) were not readily discernible on some photologs. Finally, field reviews of critical sites are essential in identifying locations where improvements are to be made and in establishing the proper type of remedial action.

SUMMARY AND CONCLUSIONS

An attempt has been made to describe New Mexico's rural single-vehicle, fixed-object accident experience and to develop a procedure, using the rate quality control method, of identifying roadway sections that have unexpectedly high fixed-object accident rates. Although this procedure has been applied here to a particular accident type, it should be realized that the process is applicable to most accident subsets with sufficient sample size. The process has, in fact, also been used to examine single-vehicle, run-off-the-road accidents on New Mexico's secondary system (6).

However, several concerns regarding the use of this procedure should be recognized. First, there may be roadway sections that have accident rates just below critical; changing the statistical level of significance, then, will affect the number of sections identified as critical. Second, it would appear from an examination of the New Mexico data that the locational information in the roadway inventory file is superior to that in the accident record system; incorrect milepost coding of an accident location could thus affect the rate for that section. Third, it is entirely possible that a completely different group of sections would be identified as critical if other accident subsets were considered. A comprehensive program of roadside safety in the state should thus recognize the importance of these other accident types. Finally, it should be realized that past accident experience is not the only reliable indicator of hazard. Past accidents cannot be eliminated; with proper evaluation and development of countermeasures, however, the number of future accidents may be reduced.

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A Nonparametric Quasi-Experimental Technique for Evaluating Highway Traffic Safety Countermeasures

JESSIE C. FORTENBERRY, DAVID B. BROWN, and DAVID M. RHYNE

ABSTRACT

A nonparametric quasi-experimental time series analysis is presented as a method for circumventing many of the problems often encountered in applying statistical analysis to the evaluation of safety programs. It is shown how this method is applicable where classical experimental techniques are impossible to implement. A case study, which shows the application to an actual pedestrian program evaluation, is given to exemplify the technique.

Under ideal conditions, experiments are set up in such a manner that by varying certain factors under controlled conditions, observation can be made as to the effects of the factors involved. The manner in which these factors are combined, the sequence in which they are observed, and the conditions under which they are controlled constitute the experimental design. Unfortunately, not all situations that need evaluating lend themselves to the controls that are dictated by classical experimental design. It is not always possible to randomly assign treatment conditions or to control unknown factors. Under these circumstances, a "quasi-experimental" design may be considered.

A quasi-experimental design describes how observations can be made under constraints imposed by nonlaboratory environments. The primary concern is to isolate the effects of interest from outside influences. For evaluation studies, effects of interest are the impacts that a program has on the performance measures under consideration. The quasi-experimental design attempts to maximize the extent to which these effects can be measured without contamination from other effects such as historical trends, seasonal influences, parallel activities, or universal random effects. Under this design, the philosophy is simply to measure performance parameters in such a manner as to eliminate alternative explanations (other than program effects) for any change observed.

Conceptually, the situation consists of a time series of N observations as follows:

$$O_1 \quad O_2 \quad O_3 \quad O_4 \quad O_5 \quad O_6 \quad O_7 \quad \cdots \quad O_N$$

At some point in the time series, an intervention for a treatment area is observed at the point where the treatment is initiated.

$$O_1 \quad O_2 \quad O_3 \cdots O_M \mid O_{M+1} \quad O_{M+2} \quad O_{M+3} \cdots O_N$$

TREATMENT INITIATED

Here, N observations are taken with M observations occurring before the treatment is introduced and N - M observations occurring after the treatment. The first M observation can be considered as a base period and the N - M observations can be considered as constituting an operational period.

With such a time series of observations, analysis can be performed by measuring performance measures before and after a treatment condition is introduced. In a fairly stable environment, this type of analysis should be able to detect any effects that the treatment condition has on the performance measures. However, just because analysis of a time series of observations detects a change in performance measures that coincides with the initiation of a treatment program does not necessarily indicate that the change was due to the treatment. An evaluation must be able to first assess the effects of a treatment condition and then eliminate alternative explanations for such change.

One method of logically eliminating some alternative explanations for change is to use a control. This would consist of two time series of observations--one for treatment and one for control--as follows:

	Pre Treatment	Post Treatment
Control Area	$O \quad O_{12} \cdots O_{1m}$	$O_{1M+1} \; O_{1M+2} \cdots O_{1N}$
Treatment Area	$O_{21} \; O_{22} \cdots O_{2M}$	$O_{2M+1} \; O_{2M+2} \cdots O_{2N}$

This experimental design can handle a number of situations provided that adequate control areas and sufficient time periods are selected. Note that in this paper, an "ideal control area" is one that is identical in all aspects to the treatment area with the exception of treatment program. Obviously, this situation does not exist in the nonlaboratory environment. The next best thing is to select a control area that is similar to the treatment area in as many factors as possible. [For a more complete discussion of quasi-experiment design, see Caporaso and Roos (1).]

TECHNIQUE

The objective of this type of evaluation is to accurately compare the actual data for the operational period with what could reasonably be expected based on the data of the baseline period. The assumption is made that if the project intervention had not taken place, then the data for the operational period would be an undisturbed continuation of the data for the baseline period. A regression model is constructed as an effort to accurately project what can reasonably be expected for the operational period based on the data of the baseline period. These projected values are then compared with the actual data in evaluating the effect that the program intervention had on the data.

A new evaluation technique was developed that consists of a unique combination of two well-known evaluation procedures, linear regression and the Wilcoxon Test. It was developed from the concepts of the quasi-experimental design and the need for comparing a time series of data following program initiation to a time series of data that would have been expected had a program not occurred. It also involves the use of a control area to prevent uncontrollable factors from giving a false indication of program effectiveness.

One of the assumptions of regression models is that variability of the data is symmetrically distributed about the line of regression of y and x. If this assumption holds, then it is equally likely that the data will fall above the regression line as below the regression line. Now, if regression models were constructed for both a treatment area and a control area, then it also would be equally likely that as many of the data points for the control area will fall below the regression line as for the treatment area. Not only are the data points equally likely to fall above as below the regression line, but they should also be equally distributed about the regression lines in terms of magnitude when adjusted by their standard error of estimate. In other words, it is equally likely that x number of data points will fall +2 or more standard-error-of-estimate points below the regression line for the control area as for the treatment area.

The fact that the linear regression for one area may account for a larger proportion (R^2) of the variance than the linear regression for the other area does not present a problem for the technique. Even if the accounted variance for one area is smaller than for the other area, the remaining variability of the data is symmetrically distributed about the line of regression of y on x. The magnitude of this variability is then adjusted by its standard error of estimate. A large symmetrical variability about the regression line does not affect the test statistic. It is only when a set of data becomes unsymmetrical about the regression curve that the test statistic is affected. In other words, the test statistic is affected whenever there is a shift in the general trend in the data for one area and there is no corresponding shift in the general trend for the other area.

To evaluate a treatment area, the deviations (actual data minus forecasted data) from both the treatment area and the control area are converted to Z values (deviation-standard error of estimate). The data then consist of n' paired observations (Z_{T1}, Z_{C1}), (Z_{T2}, Z_{C2}), ..., (Z_{Tn}, Z_{Cn}), where Z_{Ti} is the Z value for the treatment area for the ith month and Z_{Ci} is the Z value for the control area for the ith month. The absolute differences (without regard to sign), which can be represented as

$$Di = |Z_{Ci} - Z_{Ti}|;\ i = 1, 2, \ldots, n' \tag{1}$$

are then computed for each of n' pairs (Z_{Ti}, Z_{Ci}). The differences (Di's) are ranked from 1 to n' according to their absolute values.

If the common median of the Di's is denoted by $D_{.50}$ and the test is one-tailed, then the hypotheses may be stated as

$$H_0 : D_{.50} \leq 0$$

$$H_1 : D_{.50} > 0$$

The alternative hypothesis may be stated in words as "The values of Z_{Ti}'s tend to be smaller than the values of Z_{Ci}'s." The test statistic (T) is the sum of the ranks of the positive Di's. Large values of T indicate that H_0 is false, so, reject H_0 at the level of significance α if T exceeds $W_{1-\alpha}$,

$$W_{1-\alpha} = [n(n+1)/4] + X_{1-\alpha}\{[n(n+1)][(2n+1)/24]\}^{1/2} \tag{2}$$

where $X_{1-\alpha}$ is the pth quantile of a standard normal random variable.

METHOD

The procedure for conducting a Linear Regression-Wilcoxon Test are given in the following steps. [For a discussion of the Wilcoxon Test, see Conover (2).]

1. Perform a linear regression on the time series data for the baseline period of the treatment area where the dependent variable is the evaluation metric of concern, and the independent variable is the numbered time period so that

$$y_t' = a_t + b_t X \tag{3}$$

2. Perform a similar linear regression on the time series data for the baseline period of the control data so that

$$y_c' = a_c + b_c X \tag{4}$$

3. Compute the standard error of estimate about the regression lines for both the control and treatment areas so that

$$S_t = \{(1/n-2) \sum_{i=1}^{M} [y_{t_i} - (a_t + b_t X_i)]^2\}^{1/2} \tag{5}$$

$$S_c = \{(1/n-2) \sum_{i=1}^{M} [y_{c_i} - (a_c + b_c X_i)]^2\}^{1/2} \tag{6}$$

4. Compute regression values for each time interval in the operational period for both the control and treatment areas so that

$$y'_{t_j} = a_t + b_t X_j \quad \text{for } j = M + 1 \text{ to } N \tag{7}$$

$$y'_{c_j} = a_c + b_c X_j \quad \text{for } j = M + 1 \text{ to } N \tag{8}$$

5. For each time period in the operational period, subtract the actual data point from the regression value for that period and area so that

$$d_{t_j} + y_{t_j} - y'_{t_j} \quad \text{for } j = M + 1 \text{ to } N \tag{9}$$

$$d_{c_j} = y_{c_j} - y'_{c_j} \quad \text{for } j = M + 1 \text{ to } N \tag{10}$$

6. Divide the values obtained in step 5 by the standard error of estimate for the respective area so that

$$z_{t_j} = d_{t_j}/S_t \quad \text{for } j = M + 1 \text{ to } N \tag{11}$$

$$z_{c_j} = d_{c_j}/S_c \quad \text{for } j + M + 1 \text{ to } N \tag{12}$$

7. Subtract the value obtained in step 6 for the treatment area from that obtained for the control area for each time period so that

$$D_j = Z_{c_j} - Z_{t_j} \quad \text{for } j + M + 1 \text{ to } N \tag{13}$$

8. Rank the difference obtained in step 7 according to their absolute values.
9. Add the rankings of the positive differences. This is the test statistic (T).
10. If T exceeds

$$W_{1-\alpha} = [n(n+1)/4] + X_{1-\alpha} [n(n+1)(2n+1)/24]^{1/2}$$

where $X_{1-\alpha}$ is the 1-αth quantile of a standard normal random variable, and n = the number of time intervals in the operational period, then reject Ho at the α level of significance and conclude that data for the treatment area were significantly different from that of the control area.

EXAMPLE

Data are presented here to illustrate the evaluation technique. These data were taken from a pedestrian program for which the nature and the effectiveness have been reported elsewhere (3). The pedestrian program was of an educational nature involving 6- and 7-year-old children in four major cities of Alabama. Accident data for the 6- and 7-year olds constituted the treatment observations and accident data for the other age groups within the four-city area were used as the control. These data are presented in Tables 1 and 2, respectively. The pedestrian educational program began in the fall of 1978; therefore, October 1 was used as the program intervention point for the treatment area.

TABLE 1 Pedestrian Accident Data for 6-7 Year Age Group

Month	1976	1977	1978	1979	1980
January	2	2	6	6	5
February	3	7	6	0	1
March	6	3	6	0	3
April	5	5	7	3	5
May	11	7	5	3	3
June	3	8	3	4	6
July	4	3	2	1	6
August	5	4	8	3	3
September	6	5	7	5	4
			I		
October	7	4	8	2	-
November	6	6	3	2	-
December	3	3	2	4	-

Note: I = intervention. This refers to the point in time at which the pedestrian educational program began.

TABLE 2 Pedestrian Accident Data for All Other Age Groups

Month	1976	1977	1978	1979	1980
January	79	34	41	43	42
February	61	41	39	33	38
March	53	37	46	49	40
April	49	38	60	40	52
May	55	57	52	38	45
June	39	35	49	51	38
July	50	44	52	42	44
August	40	44	51	44	35
September	40	54	48	46	54
October	56	56	60	57	-
November	54	47	41	56	-
December	45	55	38	48	-

When the preceding technique was applied, the following regression equation was obtained for the treatment data:

$$y_t = 4.76894 + .02072\ X$$

with a standard error of estimate

$$S_t = 2.0963.$$

The regression equation for the control data was

$$y_c = 47.15150 + .02674\ X$$

with a standard error of estimate

$$S_c = 7.5727.$$

The remainder of the steps were carried out yielding a test value of

$$T = \Sigma R(+) = 227$$

which was statistically significant at the .05 level.

DISCUSSION

Few safety programs can be evaluated according to procedures used in a fully controlled laboratory experiment. In a field-type experiment, it is seldom possible to control, and often difficult to even identify and monitor, all the factors that could conceivably affect an experiment. Even when considerable time and effort are spent and the most sophisticated methods are used it still must be recognized that alternative explanations may exist and that the conclusions may not be as strong as if they had come from a laboratory experiment. On the other hand, a strong conclusion from a laboratory experiment may not be relevant in the real world where factors may be uncontrollable.

The technique presented herein is simple and easy to use in the evaluation of field experiments. However, as with the evaluation of any field experiment, considerable judgment must be used in the interpretation of significant results. Efforts must be made to identify and check as closely as possible all factors that could provide an alternative explanation to any effects found in the data.

ACKNOWLEDGMENT

Partial financial support for this research was provided by the Alabama Office of Highway and Traffic Safety.

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Studies on Vehicle Guidance and Control

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ABSTRACT

For approximately 10 years, part of the research effort of the TNO Institute for Perception has been devoted to the analysis and modeling of driving behavior. In this paper, some of the most relevant research issues in this area will be reviewed. First, an impression is given of some theoretical and experimental studies on course perception and vehicle guidance in preview. Second, two nearly developed methods for describing vehicle control as a supervisory task are discussed. The predictions made with these models were verified in a field experiment in which subjects drove under conditions with temporary occlusion of visual input at different speed levels. Subjects' self-chosen occlusion durations could very well be explained by both models. Suggestions are given of how the proposed methods can be applied to optimize roadway and vehicle characteristics.

For approximately 10 years, part of the research effort of the TNO Institute for Perception has been devoted to the analysis and modeling of driving behavior. In this paper, some of the most relevant research issues in this area will be reviewed. They all start from the basic view that the driver behaves as an information-processing system, looking for relevant input data in order to be able to process the course and speed of his own and other vehicles and, accordingly, to act in the right way. The issues to be discussed concern basic performance while the results of both offer elements in modeling driver behavior.

VEHICLE GUIDANCE

Much of the research into the basic perceptual cues in driving has been concerned with the perception of owner vehicle movements (i.e., the perception of course and speed) for the straight road situation. Instead of starting from a bird's-eye view description, which is the common approach in most of the presently available driver models (1-4), the purpose has been to describe and analyze the situation from a perspective view of the road ahead. Figure 1 shows an impression of the driver's visual scene looking ahead on a straight road marked with continuous lines.

In this figure, a lateral position deviation, Δy, can be optically perceived by the driver as an angular deviation $\Delta\alpha$ (5). The ratio between $\Delta\alpha$ and Δy gives a theoretical estimate of the driver's sensitivity for the perception of lateral position deviations. This ratio changes as a function of (a) the driver's eye height above the delineation, h, and (b) the driver's lateral distance to the delineation, y, according to Equation 1 as follows:

$$\Delta\alpha/\Delta y = h/(h^2 + y^2) \quad (1)$$

Figure 2 shows a representation of Equation 1, illustrating the effect of four road delineation systems on the driver's theoretical sensitivity for lateral deviations. The four delineation systems are panel-mounted (L_1 and L_2, respectively, with relative eye heights h = -0.10 m and h = 0.40 m), post-mounted (L_3, with h = 0.75 m), and pavement (L_4, with h = 1.25 m).

This analysis turns out to be of great help in understanding and explaining real-world observations, in predicting the kind of difficulties that may arise, for instance, with work-zone delineation systems, and in making recommendations. Schwab and

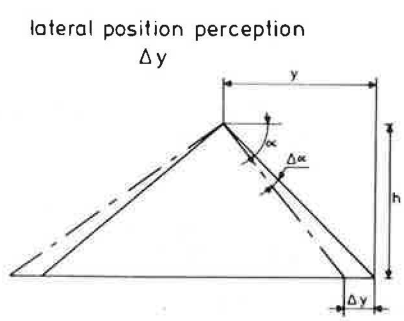

FIGURE 1 View of the road in perspective.

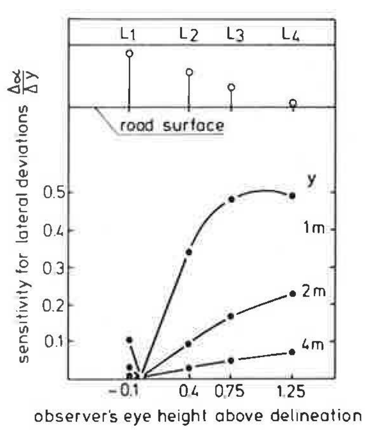

FIGURE 2 Sensitivity of lateral position perception, $\Delta\alpha/\Delta y$, as a function of the observer's eye height above the delineation, h, and different values of lateral distance to delineation, y.

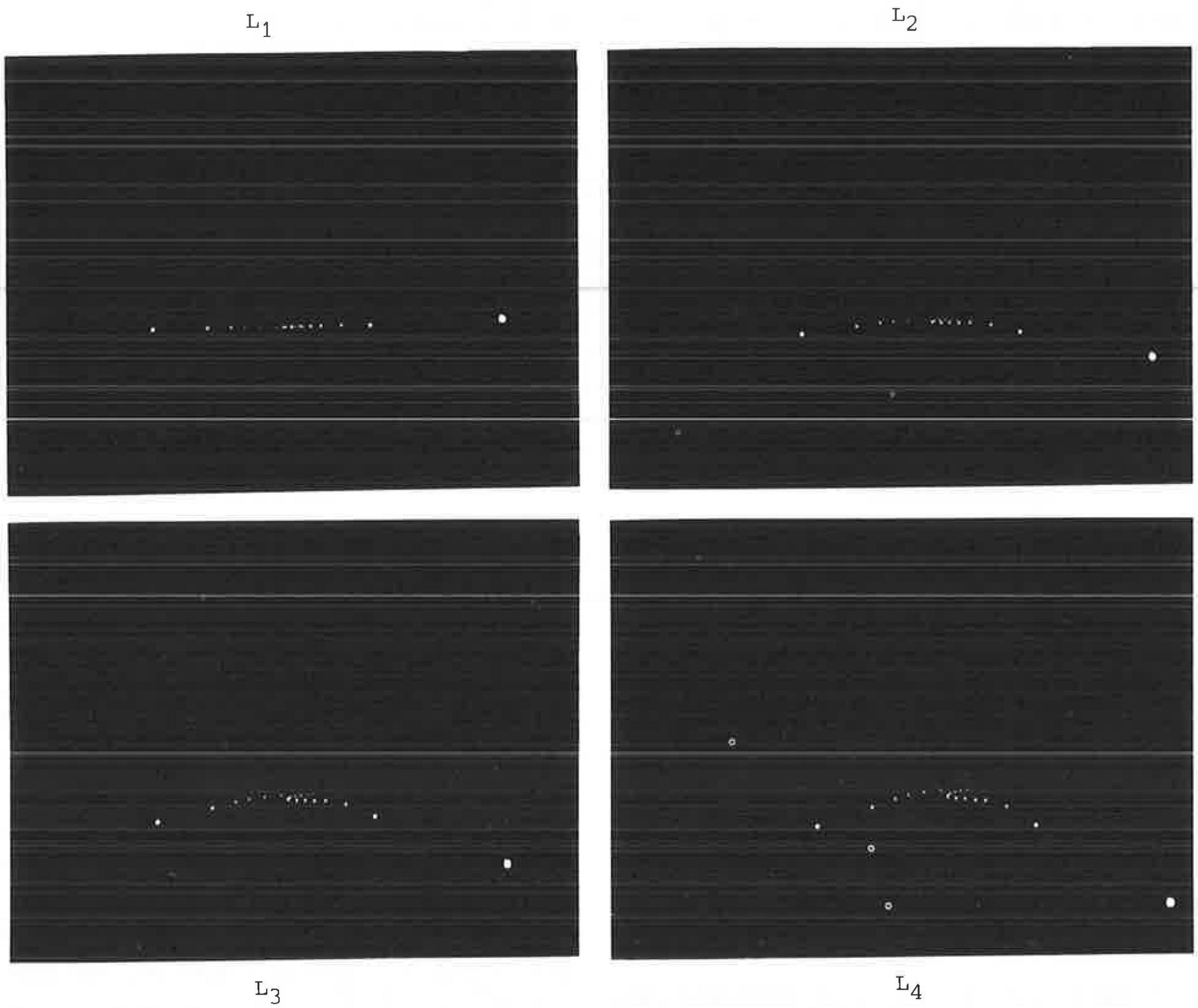

FIGURE 3 Perspective view on the geometry of the road ahead with four systems of delineators of the same geometry.

Capelle (6), for example, found that centerline delineation is highly cost-effective in terms of accident rates and driving performance. In a laboratory experiment, Godthelp and Riemersma (7) showed that there is a large effect of delineation systems varying in height on subjects' error percentages when they judged the simulated work-zone geometries shown in Figure 3. Furthermore, the results, which are presented in Figure 4, show that disturbances such as having some delineators removed from the scene (as is often the case in real situations) may strongly affect the error score. Response times of subjects were also in line with these findings; the higher the eye height above delineation, the shorter the response times in judging work-zone geometry.

The latter findings point to the effect of road delineation on the driver's preview, which is of utmost relevance for anticipation of the road geometry ahead. Early anticipation will allow timely steering performance and so will contribute to traffic safety.

VEHICLE CONTROL

One of the main tasks of the driver when steering his vehicle along the road or through a terrain is to control lateral position. Most of the available

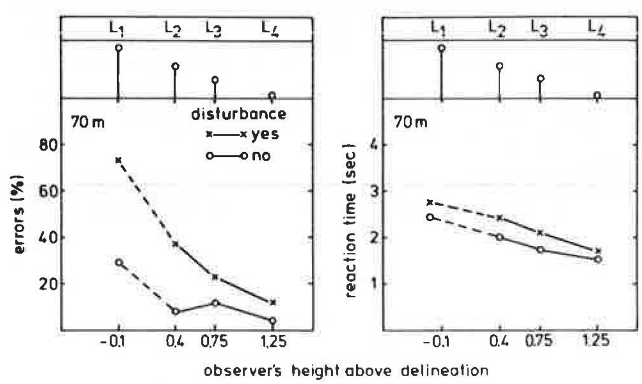

FIGURE 4 Mean error percentages and reaction times for judging the work zone geometries shown in Figure 3.

steering control models are based on the assumption that the driver acts as an error-correcting mechanism continually allocating attention to the steering task. However, driving cannot simply be considered to be a continuous closed-loop task. First, the driving task does not require permanent error control; second, the driver is sometimes forced to pay attention to aspects other than steering, so that it

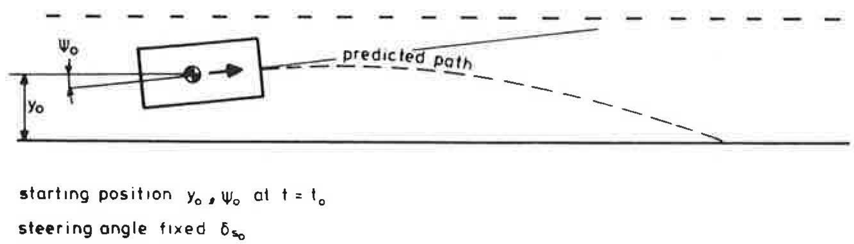

FIGURE 5 Scheme of path predictions in a preview-predictor model.

is even impossible to drive in a continuous closed-loop fashion. Hence, driver models should assume supervisory rather than continuous control. Although several uncertainty models have been developed (8-10), more research in driver modeling is necessary to obtain sufficient insight into the attentional demands of driving and the effects of vehicle and roadway characteristics.

In this paper, two methods will be discussed for the description of driving as a supervisory control task. With both methods, predictions can be made of the driver's spare time beyond the actual steering task. First, with the time-to-line crossing (TLC) approach, predictions can be made on the basis of a preview-predictor model about the time periods during which, for instance, path errors can be neglected. Second, the Optimal Control Model approach (11,12) enables predictions of "free" periods in the observation strategy of drivers during lateral position control.

Time-to-Line Crossing (TLC)

Predictions based on preview-prediction models mostly assume fixed steering control. This is shown in Figure 5. At any moment, the future path of the vehicle is predicted assuming that (a) the vehicle starts from its momentary lateral position, y_o, and heading angle, ψ_o, and (b) the steering wheel remains fixed at its momentary value, δ_{so}.

These path predictions will enable estimates of whether the driver may proceed with, or switch to, a fixed steering strategy. TLC thus defines the time needed by the vehicle to reach either edge of the lane (13). At any moment, TLC can be calculated from the vehicle's lateral position, heading angle, speed, and commanded steering angle. Figure 6 is an example of a time history of these signals together with the TLC measure. TLCs for predictions to the left (centerline) and right (shoulder line) are respectively given above and below the zero axis. Godthelp and Konings (13) argued that TLC may be helpful in describing and evaluating intermittent error-control (or error neglection) and visual open-loop strategies in driving. These strategies can be quantified by using a visual occlusion device that enables subjects to drive with self-chosen occlusion durations.

The Optimal Control Model (OCM)

The OCM describes the driver as a combined observer-predictor, controller, and decision maker (Figure 7), thus enabling the prediction of the observation and control strategy of the driver acting as a multiple-task system supervisor (14).

The driver receives information on the vehicle's position via the display variables, $\underline{y}$, and generates control actions by the vector, $\underline{z}$. The "observation-prediction block" transforms the available input information into estimates of the momentary state of the system including the estimation error (uncertainty). This transformation is made possible with knowledge of the system and display dynamics and compensates for the observation noise $V_{\underline{y}}$ of each display variable, that is, the noise-to-signal ratio for various driving situations (i.e., daytime, nighttime, fog). When no attention is paid to the display variables (e.g., during temporary visual occlusion), the observation noise is defined to be infinite. The control block transforms the internal estimates via an optimization criterion into control actions (e.g., steering wheel movements). With the help of the optimization criterion, the driver is able to evaluate, for instance,

variations in lateral position because of lane width.

The supervisory control model found its operationalization by the optimal control model MANMOD (15) and focuses on the prediction of visual "occlusion" times during which no observations are made for refreshing the driver's internal representation.

EMPIRICAL VERIFICATION

Method

Predictions of occlusion times were made with both the TLC and OCM analysis. Model predictions were compared with experimental data of subject's self-chosen occlusion durations as measured during straight road driving with an instrumented car (16). This experiment was conducted on an unused four-lane divided highway over a distance of 2 km and with a lane width of 3.5 m. Half of the runs were performed with normal vision, whereas in the other half, visual occlusion was given by a visor, which could be raised (open) and lowered (closed) on command of the subject. In its normal state, the visor was closed, but on pressing the horn lever, the visor would rise and stay open for 0.55 sec. Measurements were made on steering wheel angle, yaw rate, lateral position, and occlusion times. TLCs were calculated for each sample (4 Hz).

TLC Predictions

Median and 15th-percentile TLC values were calculated together with means and standard deviations of lateral position, lateral speed, and steering wheel angle. Table 1 gives the results of these measures for six different speed conditions. Of main interest,

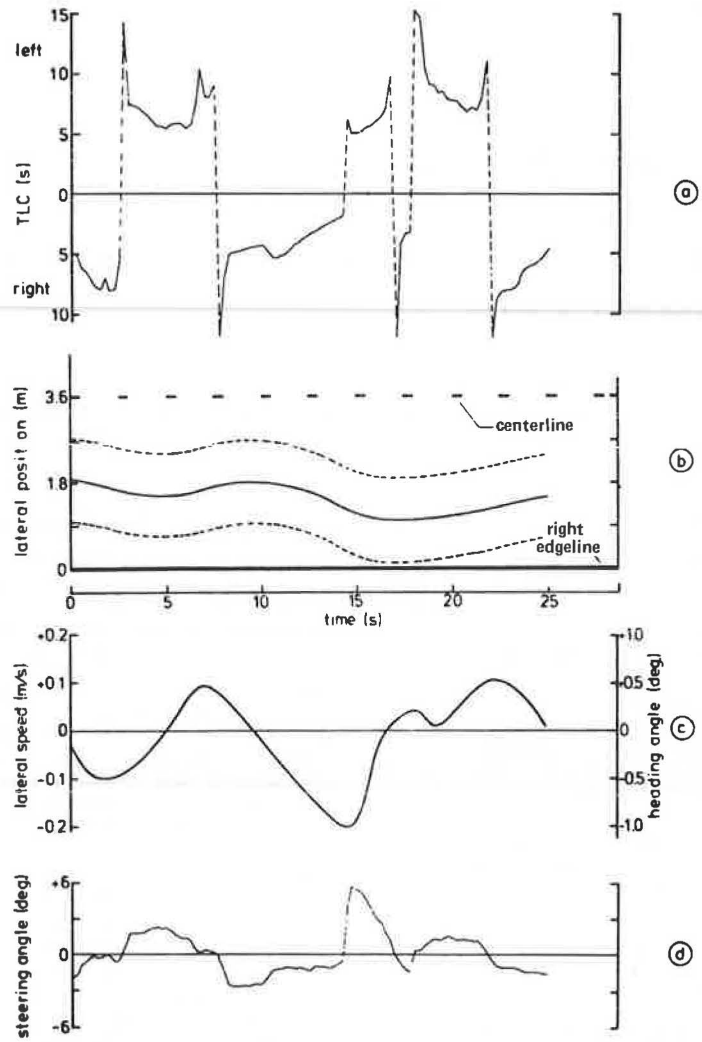

FIGURE 6 Sample time history of TLC (a), resulting from the corresponding lateral position (b), lateral speed (c), and steering-wheel angle (d).

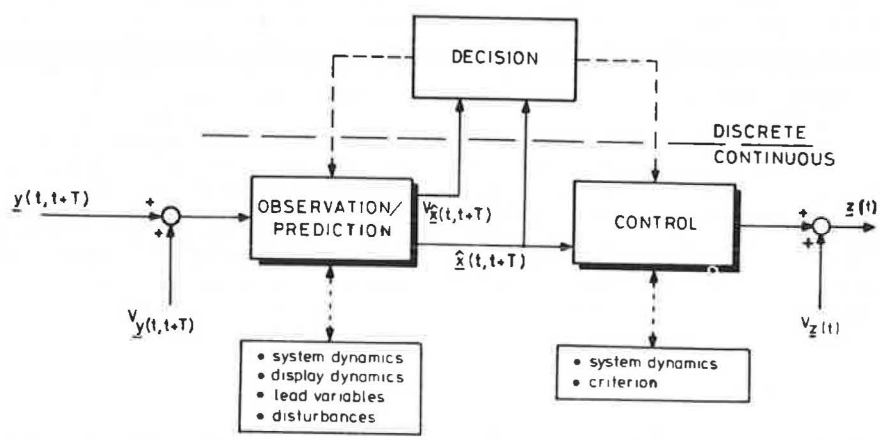

FIGURE 7 Structure of the supervisory driver model *(14)*.

TABLE 1 Lateral Position, Lateral Speed, and Steering Wheel Angle Values as Affected by Vehicle Speed and Visual Occlusion *(15)*

Speed (kph)	20	40	60	80	100	120
Lateral position occlusion (m)						
Mean						
With	1.75	1.78	1.81	1.86	1.94	1.94
Without	1.80	1.78	1.76	1.82	1.77	1.88
Standard deviation (m)						
With	0.26	0.23	0.25	0.23	0.23	0.24
Without	0.12	0.13	0.16	0.15	0.16	0.16
Lateral speed						
Standard deviation (cm/sec)						
With	6.6	7.6	9.4	10.1	11.9	12.5
Without	2.3	3.7	5.1	6.0	6.7	8.0
Steering wheel angle						
Standard deviation (degrees)						
With	3.0	2.0	1.7	1.5	1.5	1.5
Without	1.2	0.9	0.9	1.0	1.1	1.2

Note: kph = kilometers per hour.

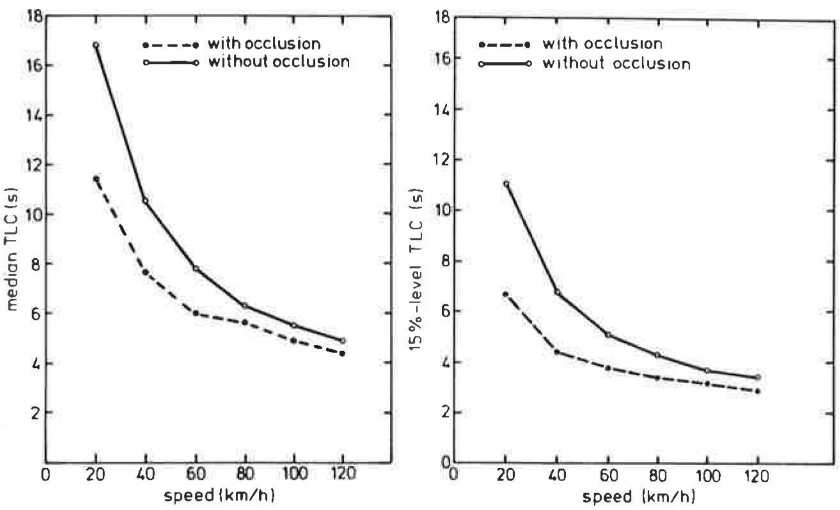

FIGURE 8 Median and 15th-percentile TLC-values as a function of vehicle speed and for runs with and without occlusion.

however, is the relation between the data of Table 1 and the TLC measure by which lateral position, speed, and steering wheel data can be integrally evaluated. Figure 8 shows that TLC is relatively large for low speeds and becoming less dependent on speed when speed increases.

The major reason for developing a time-related measure such as TLC was an interest in the relation between this measure and drivers' open-loop performance (i.e., the duration of the self-chosen occlusion intervals). The relationship between the 15 percent TLC level and the mean of the occlusion times is shown in Figure 9, thus illustrating the potential power of the TLC measure as a predictor of the driver's occlusion strategy.

Figure 10 shows a hypothetical time history of a driver's visual sampling behavior and corresponding TLC. It is clear that, just before the request for a new visual input, there is spare time before which the vehicle would have reached either one of the lane delineations. Hence, this spare time, noted as TLC_e, combined with T_{occ} gives the total time available from the start of the occlusion period until the moment one of the lane boundaries would have been reached.

An interesting finding concerns the ratio between T_{occ} and the sum of T_{occ} and TLC_e, the results of which are given in Table 2. It is evident from the data in Table 2 that this ratio appears to be remarkably constant over a large range of vehicle speeds (no significant differences; $p > 0.20$).

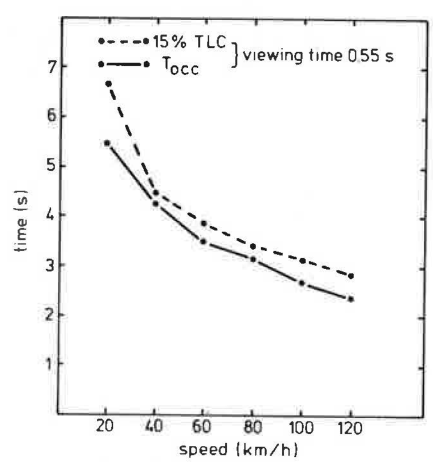

FIGURE 9 Means of occlusion times, T_{occ}, and 15th-percentile TLC-values.

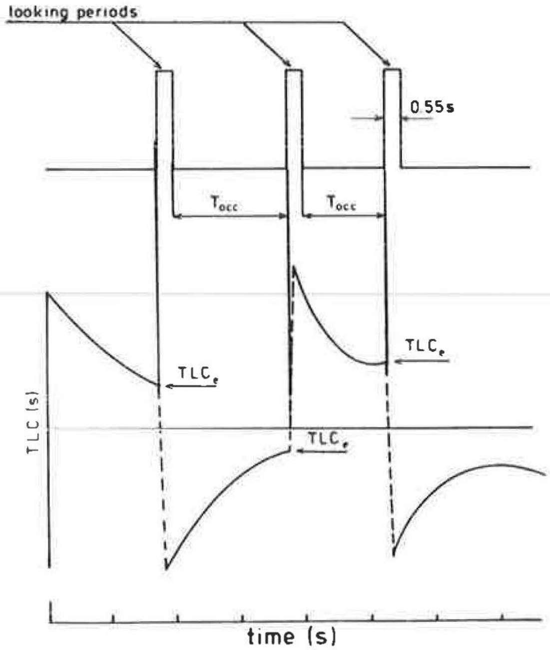

FIGURE 10 Hypothetical time history of a driver's visual sampling behavior and corresponding TLC, illustrating the points at which TLC_e values are determined.

TABLE 2 Median Values of T_{occ}, TLC_e, and Ratio $T_{occ}/(T_{occ} + TLC_e)$

Speed (kph)	T_{occ} (s)	TLC_e (s)	$T_{occ}/(T_{occ} + TLC_e)$
20	5.32	8.88	0.37
40	4.23	6.33	0.40
60	3.45	5.32	0.40
80	3.15	4.77	0.41
100	2.67	4.35	0.39
120	2.38	3.74	0.40

Note: kph = kilometers per hour.

OCM Predictions

All system dynamics for the model predictions were based on the lateral dynamics of the instrumented vehicle (14,16). Combinations were made from the following display variables: lateral position (equals inclination angle α in perspective view of the road--see Figure 1), lateral speed (equals rate of change $\dot{\alpha}$ of inclination angle), yaw rate r, lateral acceleration a_l, and yaw acceleration $\dot{r}$. The model calculations started from the following basic assumptions: no time delays or thresholds, no external disturbances, a perfect internal model of the vehicle dynamics, equal observation noise levels for the various perceptual cues, and weighing coefficients only for display variables and steering wheel rate. The weighing coefficients for the display variables were chosen to be inversely proportional to the square of the corresponding tolerated variations based on the lane boundaries for lateral position or on the measured standard deviations for the other variables (14).

Figure 11 shows the predicted standard deviations of the lateral position of the vehicle as a function of observation noise level, for six combinations of display variables in the observation-prediction block of the model. For all combinations, driving speed was 100 kph. The optimization criterion in the control block was set according to weighing of lateral position (i.e., inclination angle α).

Figure 11 also shows smaller standard deviations of lateral position for lower observation noise levels (i.e., when the state of the vehicle can be estimated more accurately). In comparison with the use of lateral position only (i.e., inclination angle α, as shown in curve 1 of Figure 11), it appears that the addition of yaw rate, r, lateral acceleration, a_l, and yaw acceleration, r, only gives marginal improvements of approximately 1-2 cm in lateral control performance (curves 2 and 3). However, the addition of the lateral speed cue in the observation-prediction block (curve 4) leads to a general improvement of a 10-cm decrease in standard deviation of lateral position. The addition of yaw rate, lateral acceleration, and yaw acceleration again leads to marginal improvements of approximately 1-2 cm (curves 5 and 6).

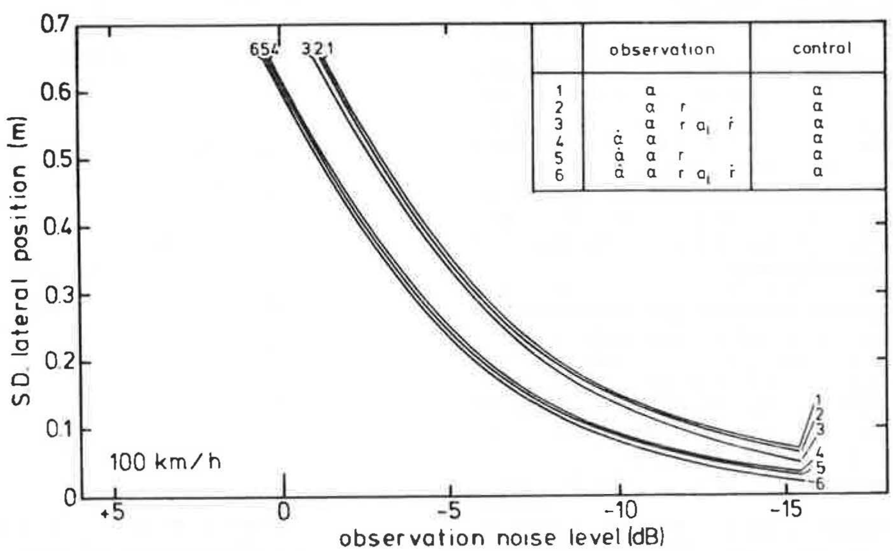

FIGURE 11 Predicted standard deviations of lateral position (via α) as a function of observation noise level for six combinations of display variables.

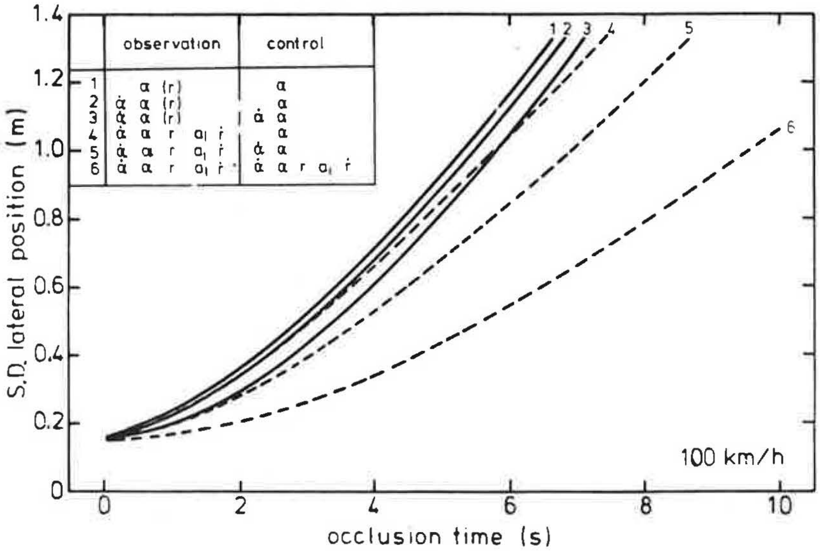

FIGURE 12 Predicted standard deviations of lateral position during visual occlusion, for six combinations of display variables.

It is also clear that more display variables can be weighed according to the optimization criterion in the control block than lateral position alone. Addition of lateral speed only has a marginal effect; yaw rate or both acceleration cues may lead to a 5-10 cm deterioration in standard deviation of lateral position.

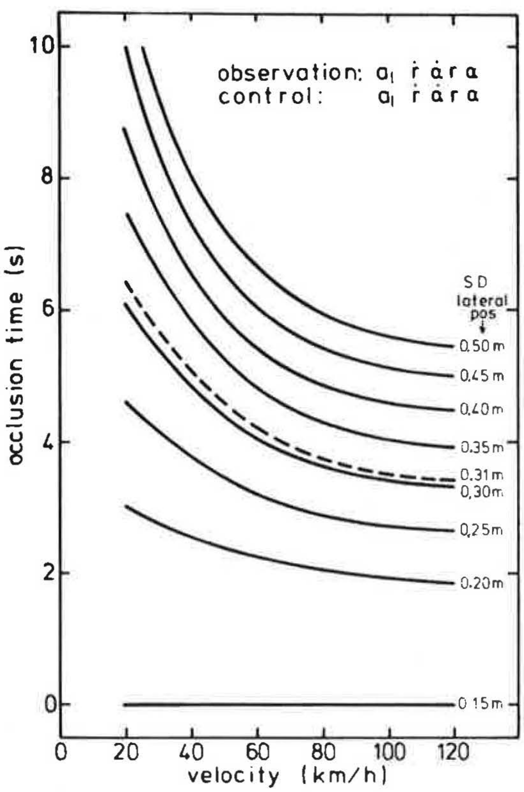

FIGURE 13 Occlusion time as a function of driving speed for constant standard deviation levels of lateral position during observation and control of all five display variables.

The model analysis can be used for the prediction of free periods in the observation strategy while controlling lateral position. Those free periods are reflected by voluntarily chosen visual occlusion durations. During occlusion periods, the driver's estimate of the state of the vehicle has to be based on knowledge of the previously observed display variables and the estimation error will increase as a function of occlusion duration.

Figure 12 gives model predictions for standard deviations of lateral position as a function of occlusion time, for several combinations of display variables.

Larger occlusion durations correspond with larger standard deviations of lateral position. Lateral acceleration, a_1, and yaw acceleration, $\dot{r}$, both contribute to much slower deterioration of control performance. Additional weighing of $\dot{\alpha}$ contributes to considerable increase in occlusion durations (curves 5 and 6). Figure 13 shows occlusion time as a function of driving speed for various levels of constant standard deviations of lateral position (i.e., the uncertainty the driver is willing to accept).

The data in Figure 13 are assumed to represent driving behavior of experienced subjects using all available information (i.e., the five display variables) for observation and control. A standard deviation level of 0.15 m reflects nonoccluded observation or an occlusion duration of 0 sec. The 0.31-m level indicates the limit in lateral variation due to a 3.60-m lane width.

The predictions of Figure 13 can be compared with empirically found occlusion durations. It appeared that the OCM enables predictions of empirical occlusion durations within one standard deviation: the correlation between the data of Figure 14 is considerable ($r = 0.97$). Hence, it is conceivable that experienced drivers indeed use all five display variables for observation and control. (Note that in Figure 14, the field data present mean values and standard deviations of measured occlusion durations of experienced drivers.)

DISCUSSION

Both TLC and OCM analyses appear to be valid methods for the description of automobile driving in terms of a supervisory task.

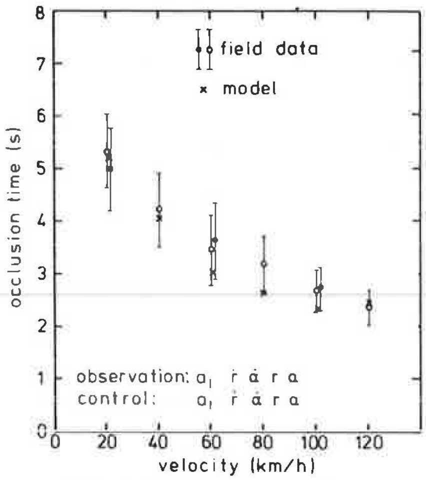

FIGURE 14 OCM predictions of mean occlusion durations as a function of speed when all five display variables are controlled.

TLC enables a quantitative time-related integral measure of driving behavior, predictions on driver's visual sampling strategy related to driving speed, predictions on the probability of lane exceedance, and a description of the relation between self-chosen occlusion durations and the total time available for occlusion. With regard to the latter possibility, it is indeed remarkable that drivers tend to use a constant proportion, approximately 40 percent, of the total available time rather than leave a constant amount of spare time at the end of the occlusion interval.

The OCM analysis enables evaluation of the potential role of various combinations of perceptual cues in driving. Use of the lateral speed cue in the observation-prediction block generally resulted in improved driving performance (i.e., smaller standard deviations in lateral position). Otherwise stated, when using the lateral speed cue drivers have more time to anticipate, while keeping control performance at the same level. Riemersma (17) suggested that the use of the lateral speed cue is an effect of driving experience. This finding was confirmed in a study by Blaauw et al. (14) who compared OCM predictions with field data of experienced and inexperienced drivers. The OCM predictions without lateral speed cue resulted in occlusion durations conforming to those of inexperienced drivers. This result is also in accordance with findings of Smiley et al. (18) who illustrated that inexperienced drivers do not only use the lateral position cue, but also yaw rate and both acceleration cues.

Both TLC and OCM analyses utilize vehicle characteristics as basic elements for predictions. Hence, it seems reasonable to apply these supervision models for the evaluation of vehicle handling properties. The models, in particular, are valuable with regard to the time-related analysis of the driver's attention needed for the driving task as affected by vehicle handling characteristics (i.e., understeering-oversteering) and vehicle dimensions.

In general, the models are applicable to such topics as the effect of various types of road markings on driving performance, the effects of driving practice, the effects of various types of road design, advice speeds, vehicle design, and the evaluation of steering properties.

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Abridgment

Impact of Drunk Driving Legislation in the State of Alabama

SAEED MAGHSOODLOO and DAVID B. BROWN

ABSTRACT

On May 19, 1980, a major revision in the Alabama driving-under-the-influence (DUI) laws went into effect, which gave judges greater discretion in sentencing. In this paper, the period before the revision of the law, in which a DUI conviction automatically resulted in revocation of the driver's license, is compared with the period after the revision. A significant increase was found in the number of DUI convictions of the after period, showing that the new law was being observed. This was accompanied by significant reductions in the number of DUI citations reduced to reckless driving, the proportion acquitted and/or dismissed, and the proportion of revocations. The law required court referral to an education program on the first offense, and these referrals significantly increased in the after period. However, the corresponding change in accidents was not favorable because there was a significant increase in the proportion of alcohol-related accidents in the after period.

On May 19, 1980, a revision of Alabama laws with regard to driving under the influence (DUI) of intoxicating liquor or narcotic drugs became effective. The basic change in the law would appear to weaken its effectiveness in that the former mandatory revocation provision was removed. The former law stated that "The director of public safety shall forthwith revoke the license of any driver upon receiving a record of such driver's conviction (of)...driving a motor vehicle...while intoxicated." This provision was modified to read as follows:

> The director of public safety shall forthwith revoke the license of any driver upon receiving a record of such driver's conviction (of)...driving...while under the influence of intoxicating liquor; providing, however, that on a first conviction such revocation shall take place only when ordered by the court rendering such conviction.

In addition to these changes, first-time offenders were required to complete a DUI court-referral educational program approved by the State Administrative Office of Courts. In addition, the law specifically states that charges cannot be reduced to reckless driving or any other offense. (The consistent use of either of the terms "DWI" or "DUI" throughout this paper would be technically incorrect because Alabama used DWI before the law change and DUI after. However, in the remainder of this paper, DUI will be used.)

Although this change might be considered a weakening of the punitive measures related to DUI, the previous circumvention of the mandatory revocation by a large number of judges in Alabama made conviction of DUI on the first offense unlikely. The resulting inaccuracy in the records made recidivism impossible to measure and, thus, multiple offenders were not being consistently punished. In fact, under the situation prior to May 1980, most offenders were

TABLE 1 Alcohol Ticket Convictions Statewide

	Convicted		Cited But Not Convicted		
	No.	Percentage	No.	Percentage	Total Cited
Before May 1980	24,988	35.03	46,353	64.97	71.347 = $n_{1.}$
After May 1980	55,149	79.74	14,016	20.26	69.165 = $n_{2.}$
Total	80,137 = $n_{.1}$		60,369 = $n_{.2}$		140,506 = N

Note: χ_0^2 = 28,646.304 and $\hat{\alpha}$ <.00001.

receiving convictions on reduced charges. A summary of the tickets compiled to date for a study in 1979 showed a conviction rate of DUI of approximately 37 percent (21,206 citations; 7,798 convictions); but while 15,431 drivers were cited for reckless driving, 21,079 were convicted of reckless driving (136.6 percent). Obviously, the previous law was not only being inconsistently (and hence unfairly) applied, it was also preventing proper maintenance of driver history records on habitual offenders. The modification of the law was intended to rectify this condition.

LITERATURE REVIEW

The problems caused by drinking drivers have been documented extensively. Cameron (1) gave the history of driving under the influence of alcohol dating back to the first automobile. Approximately one-half of all driving fatalities occur when the driver has a blood alcohol content (BAC) of 0.1 percent or higher, according to Johnston (2). Considerable work has been done in the area of creating and evaluating DUI countermeasures. Some of the countermeasures involve the prevention of sales of beverages to those who are intoxicated, while other programs center on an educational and motivational approach to the driver. Hayslip, Kapusinski, Darbes, and Zeh (3) discussed certain of these DUI programs.

Over the past 20 years, the arguments over harsher sentences as opposed to educational programs have persisted. A comparison of license revocation versus alcohol treatment was made by NHTSA (4). License revocation seemed to be the most effective alternative among habitual offenders (more than 3 offenses in 5 years). As for an evaluation of more severe penalties, Moore and Gerstein (5) discussed the British Road Safety Act. Results of this program were amazing, at first. In the first three months, automobile fatalities were reduced 23 percent, and the percent of drunk drivers (0.08 BAC or greater) in accidents went from 27 to 17 percent.

While the evaluational research with regard to legal changes was not definitive, one thing was clear from the literature review: there is a need for a balanced approach with regard to all of the available countermeasures being employed. Such a balance, however, requires considerable study to resolve the conflicts caused by competition by the various programs for the limited resources available. It is hoped that this paper will produce the type of information by which this balance can be more nearly optimized to bring about a maximum reduction in alcohol-related accidents.

DATA COLLECTION AND PROCESSING

Data collected and processed for this study can be classified into two categories: (a) uniform traffic citation (UTC) records, and (b) accident records. The UTC data were acquired from two sources--the primary source was the computerized UTC file maintained by the Alabama Department of Public Safety (ADPS), and the secondary source was the manually maintained summary of alcohol-related revocations, also kept by ADPS. Other sources of data were the Alabama Uniform Traffic Accident Report and the accident file maintained by the ADPS. This file contains approximately 110,000 records per year, one per accident. Processing of both UTC and accident files was facilitated by the use of the RAPID system (documentation for this system is available from the Alabama Office of Highway and Traffic Safety, Room 741, 11 South Union Street, Montgomery, Alabama 36130). RAPID enables any subset of the data to be created; in this case, the alcohol accidents or DUI tickets were usually the subset of interest. In all cases, the "before" period was from January 1978 through April 1980 (28 months), and the "after" period was from June 1980 through June 1982 (25 months). It must be emphasized that from a statistical design standpoint, it would have been more appropriate to use a 23-month (June 1978 through April 1980) before period and the corresponding months (June 1980 through April 1982) for the after period. However, the deletion of the 7-month data will not alter the results reported herein. The month of May

TABLE 2 Alcohol Tickets for Categories 2 Through 7

	Reduced to Reckless Driving		Reduced to Other Charges or Dismissed		Acquitted		Not Acquitted		Dismissed	
	No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage
Before May 1980	37,628	81.18	8,725	81.82 12.23[a]	9,145	12.81	62,196	87.19	7,736	10.84
After May 1980	7,044	50.26	6,972	49.74 10.01[a]	7,986	11.55	61,179	88.45	6,728	9.73
Total	44,672		15,697		17,131		123,395		14,464	
χ_0^2			5,347.473				53.1089			47.2575
$\hat{\alpha}$			<.00001				<.00001			<.00001

[a]These percentages were computed relative to all citations issued (e.g., .1001 = 6,972/69,165).

1980 was discarded because the revision of the law took place on the 19th of this month.

PROBLEM STATEMENT

Because there are potentially many facets of an evaluation of a legislative action, it is essential that the scope of this study be clarified before continuing. Specifically, the objectives of this paper are to investigate the effects, if any, that the change in the law had on the following categories:

1. DUI conviction rates,
2. DUI citations reduced to reckless driving,
3. Acquittals,
4. Dismissals,
5. Revocations,
6. Court referrals, and
7. Changes in alcohol-related accidents.

In the analysis that follows, when reference is made to, for instance, category 3, it refers specifically to the proportion of citations that were acquitted, similarly for categories 1, 2, 4, 5, 6, and 7.

STATISTICAL ANALYSES

The chi-square test was applied to the data to determine if the differences between the before and after periods for the preceding seven categories were significant. Before continuing, however, it should be noted that any inferential statistical technique starts with random samples from one or more populations, and the analysis attempts to generalize any differences found among the samples to the populations. In this research, the size of each sample was almost equal to that of the corresponding population and, thus, any observed differences that are not significant from a practical standpoint may be found significant from a statistical standpoint. However, if one was to consider the data in a time series mode, then the major part of the population (for the after period) would still be forthcoming, and only 28 months of the before period (out of many possible months) would be used in the analysis. It is in this light that the conclusions derived from the statistical tests should be interpreted. Furthermore, the tabulation of the data in a contingency table will help the reader to see the practical differences in the percentages provided in the table.

For the sake of illustration, a detailed description is given of the chi-square test for conviction rates with the aid of the 2 x 2 contingency table (Table 1) and the data and test results are summarized for the other six categories in Table 2. In Table 1, let P_B and P_A represent the proportion of citations that resulted in convictions before and after May 1980, respectively. It is desired to test the null hypothesis H_0: $P_B = P_A$ versus the alternative H_1: PB ≠ PA. The statistic

$$\chi^2_0 = [N(0_{11}\, 0_{22} - 0_{12}\, 0_{21})^2]/n_{1.}\, n_{.1}\, n_{2.}\, n_{.2}$$

was used to test the null hypothesis H_0: $P_B = P_A$, where 0_{ij} denotes the observed frequency in the ith row and jth column of the table. Table 1 shows that χ = 28,646.30, which is enormously significant. Thus, H is strongly rejected at the critical level

$$\hat{\alpha} = P(\chi^2_{\gamma = 1} \geq 28{,}646.30) \doteq 0$$

That is, in rejecting H_0, an almost zero chance of committing a type I error (rejecting a true hypothesis) is being taken. Therefore, it is concluded that P_A far exceeds P_B with virtual certainty. Thus, the new law was enormously successful in raising the conviction rate from approximately 35 percent before the change to almost 80 percent after.

Table 2 clearly shows that the legislative action had a similar significant effect on categories 2 through 5 (i.e., significant reduction took place in the proportion of tickets issued for alcohol-related offenses when the charges were reduced to reckless driving, citations that were acquitted, and dismissals and revocations). However, the change in the law resulted in a significant increase in the proportion of court referrals and the number of alcohol-related accidents.

INTERPRETATION OF RESULTS

The complex nature of the DUI countermeasure cause-effect mechanisms defies any simple solution to this problem. The presentation of these results to officials of the judicial and enforcement communities confirmed some of their obvious practical expectations. However, they warned against any radical action that would upset the delicate balance that now exists within the system.

To understand the situation as it currently exists within Alabama, it is necessary to first abstract the total criminal justice system as it relates to the DUI offender. The goal of this system is to totally eliminate the DUI menace to society. To approach this goal within the environment of political and societal attitudes toward the recreational use of alcohol, a primary objective of deterrence has been established. To accomplish this primary objective, secondary objectives have been established

Not Dismissed		Driver Licenses Revoked		Driver Licenses Not Revoked		Referred to School		Not Referred to School		Alcohol-Related Accidents		All Other Accidents	
No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage
63.605	89.16	32,145	45.44	38,926	54.56	7,443	10.43	63,898	89.57	35,922	12.21	258,311	87.79
62,427	90.21	17,350	25.08	51,815	74.92	11,836	17.11	57,329	82.89	30,097	13.74	189,005	86.26
126,032		49,765		90,741		192,79		121,227		66,019		447,316	
				6,359.1193			1,323.585					261.581	
				<.00001			<.00001					<.00001	

in the areas of publicity, apprehension, conviction, punitive measures, and rehabilitation. Although it might seem that a radical change in one of these areas might lead to an ideal, quick, and inexpensive solution to the problem, a favorable long-term effect will not be realized unless it has a direct impact on the primary objective of deterrence. This comes about because the result of increasing concentration on one countermeasure is not independent of the other countermeasures. Publicity and education will quickly lose much of their credibility without effective apprehension, conviction, and punitive measures. Apprehension and enforcement can similarly become ineffective if, for example, officers who, knowing that conviction and punishment are unlikely, become disillusioned and redirect their efforts to what they perceive as an area of greater demand by society, or officers (especially on the local level), recognizing that conviction and harsh punishment will surely follow, become unwilling to arrest in cases that they perceive will result in severe hardship. Rehabilitation, when it is viewed as an alternative to traditional punitive measures, may be regarded as a weakening of public resolve to place the blame for DUI on the offender as opposed to society as a whole.

It is obvious from the preceding hypotheses that because of a change in the Alabama DUI law on May 19, 1980, there was a radical increase in the proportion of DUI citations that resulted in convictions. The cause of this, however, cannot be ascribed solely to the mandate of the new law. Rather, it was another provision of the law--that which gave judges greater discretion over sentencing--that must be heavily credited, as evidenced by the inverse relationship between convictions and revocations.

Thus, this study has tended to confirm and quantify that which has been the opinion of officials within Alabama for many years. That is, the willingness of judges to convict for DUI on the first offense is largely a function of punitive measures mandated by law. Because harsher punitive measures are often cited as a deterrent to DUI accidents, it is reasonable to ask whether such measures would have a positive effect of reducing DUI accidents in Alabama.

The rationale for the law change was that consistent application of a higher conviction rate should have a positive effect in reducing the proportion of alcohol-related accidents. Unfortunately, the data in Table 2 provide evidence to the contrary. Some of the proportional increase in alcohol-related accidents, however, could be attributed to the fact that such accidents were on the rise nationwide from 1978 through 1981 and decreased in 1982 and 1983, and the change in Alabama law went into effect in the middle of a period when alcohol-related accidents were generally increasing. However, the fact that the punitive measures were weakened considerably by the law cannot be discounted as a causative factor. Alabama has since taken steps to restore the mandatory revocation provisions on the first offense, and this change will be evaluated when data are available.

To close on a positive note, it was the opinion of all officials interviewed that significant gains were made by the law change in terms of the accuracy of driver history records and the increased fairness and equity in the judicial handling of DUI cases. Consistency is essential to fairness, and the evidence presented shows that much of the former inconsistencies between judges has been eliminated. Records now accurately reflect the true conviction and, as a result, more stringent punitive measures can be taken on the second and third offenses.

ACKNOWLEDGMENT

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A Vehicle-Mounted Drunk Driving Warning System (DDWS) Concept, Laboratory Validation, and Field Test

ANTHONY C. STEIN, R. WADE ALLEN, and HENRY R. JEX

ABSTRACT

A brief manual control test and decision strategy have been developed, laboratory tested, and field validated, which provide a means for detecting human operator impairment from alcohol or other drugs. The test requires the operator to stabilize progressively unstable controlled element dynamics. Control theory and experimental data verify that the human operator's control ability on this task is constrained by basic cybernetic characteristics, and that task performance is reliably affected by impairment effects on these characteristics. Assessment of human operator control ability is determined by a statistically based decision strategy. The operator is allowed several chances to exceed a preset pass criterion. Procedures are described for setting the pass criterion based on individual ability and a desired unimpaired failure rate. These procedures were field tested with an automobile-installed apparatus designed to discourage drunk drivers from operating their vehicles. This test program, sponsored by the U.S. Department of Transportation, demonstrated that the control task and detection strategy could be applied in a practical setting to screen human operators for impairment in their basic cybernetic skills.

Reviewed in this paper are the development and validation of a behavioral testing device that can detect human operator impairment. These skills are important in performing tasks that require continuously manipulating displayed variables with a control device, such as driving or machinery operation. The manual control skills required to perform these types of tasks have been extensively studied (1), and the test described herein has been developed to detect impairment in these skills.

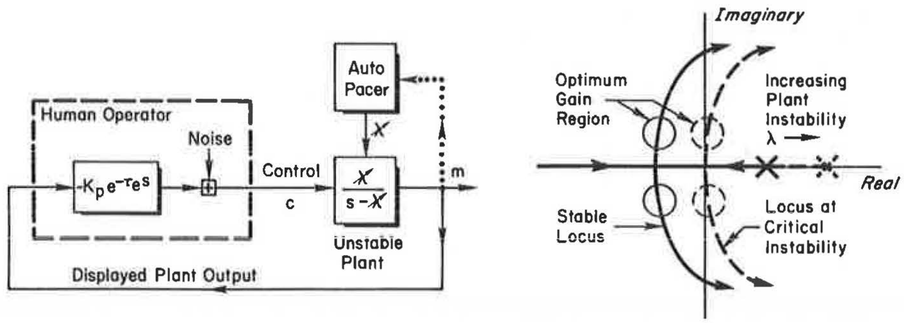
The test involves two components: a control task and a detection strategy. The control task, called the Critical Tracking Task (CTT), was developed in the early 1960s to test the visual motor performance of pilots and astronauts (2,3). Over the years, it has proven to be an effective indicator of the effects of environmental stresses [e.g., noise (4), space station confinement (5), ship motion (6), spacecraft re-entry (7), and human operator impairment (8,9)].

The use of the CTT as an alcohol impairment detection device was first tested in automobiles by the General Motors Corporation (10). Subsequent research sponsored by the U.S. Department of Transportation (11-14) was conducted to optimize the test strategy. In subsequent research, the statistical decision theory for optimizing the detection strategy was developed and validated in laboratory tests (15). Following this, vehicle-mounted devices were assigned to convicted drunk drivers to obtain field validation data (16). In the remainder of this paper, the control theory basis for the CTT will be described, as will the statistical theory behind the impairment detection strategy, and laboratory and field test results that validate tester performance in a practical, operational environment.

CRITICAL TRACKING TASK (CTT)

The task description and theory of operation for the CTT have been previously documented (2,3). A summary is illustrated in Figure 1. The task dynamics consist of an unstable controlled element, and an autopacer unit that controls the location of the unstable pole. No input is necessary because the operator's remnant (noise) is sufficient to disturb the system. The unstable root, λ, is initially set at a small value. As the subject begins to perform the task, the plant instability is increased (the root moves further into the right half plane). When a filtered version (with a 1-sec time constant) of the displayed plant output deviations, m, exceed about 15 percent of the display range, the rate of increase of λ is reduced by a factor of four in order to slowly approach the point of closed loop instability and avoid overshoot. When m exceeds the display limits, control loss is assumed, and the pole location at this point, termed the critical instability limit (or λ_c), is used as the task performance metric. The total test time for experienced subjects is approximately 30 sec.

As indicated in Figure 1, the subject's task performance depends on visual-motor dynamic time delay (τ_e), gain (K_p), and internal noise or remnant (random control actions). The subject's time delay dictates the shape of the root locus (the pure time delay causes the complex branches to bend to the right) while K_p determines the operating point on the locus. Increasing the task instability (λ) translates the entire locus to the right or unstable direction. The pure gain closure dictates two primary closed-loop roots (a pure time delay actually gives an infinite number of roots, but the lowest frequency pair dictates the stability characteristics). The operator's optimum strategy is to set K_p to locate both closed-loop poles on the imaginary axis as indicated. The task is continually perturbed by the operator's internal noise source. As the point of closed-loop instability is approached, the underdamped closed-loop system response tends to increasingly amplify display deflections, at first causing a reduction in the autopacing rate,



a) Block Diagram *b) Root Locus*

FIGURE 1 CTT task elements and root locus stability analysis.

then finally terminating a trial when the display bounds are exceeded. These theoretical aspects have been carefully validated by experiments in the United States (2,3) and The Netherlands (17).

Impairments can affect the human operator's control capability in three ways: (a) increased visual-motor time delay (τ_e); (b) interference with accurate K_p adjustments; and (c) increased noise. Any combination of these three impairment effects would tend to reduce the achievable task score, λ_c. Several studies have been conducted on the effects of alcohol on λ_c and summary results are plotted in Figure 2. As noted here, results have been extremely reliable across several past studies.

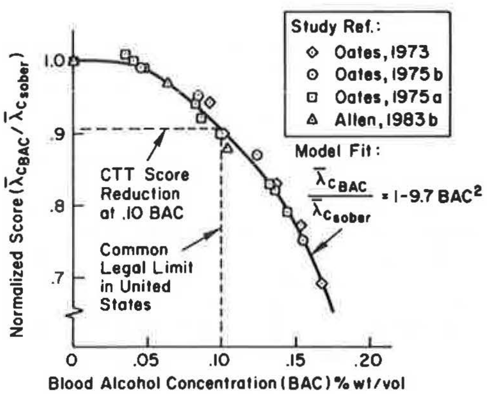


FIGURE 2 Experimental results of alcohol effects on CTT performance over several past research studies.

The critical tracking task can, of course, be described in simpler terms. The test is similar to balancing a broomstick on the end of ones' figure--only the stick decreases in length as time progresses. At some point, the stick is too short to balance, and it falls over. The length of the stick when control was lost is compared to the individual's unimpaired ability, and if certain criteria are not met, the trial is failed. If the driver fails four trials in a row, the alarms (flashers and horn) stay active and the driver must wait 10 min before attempting the test again. If any one of the trials is passed, the alarms are shut off and the car operates normally.

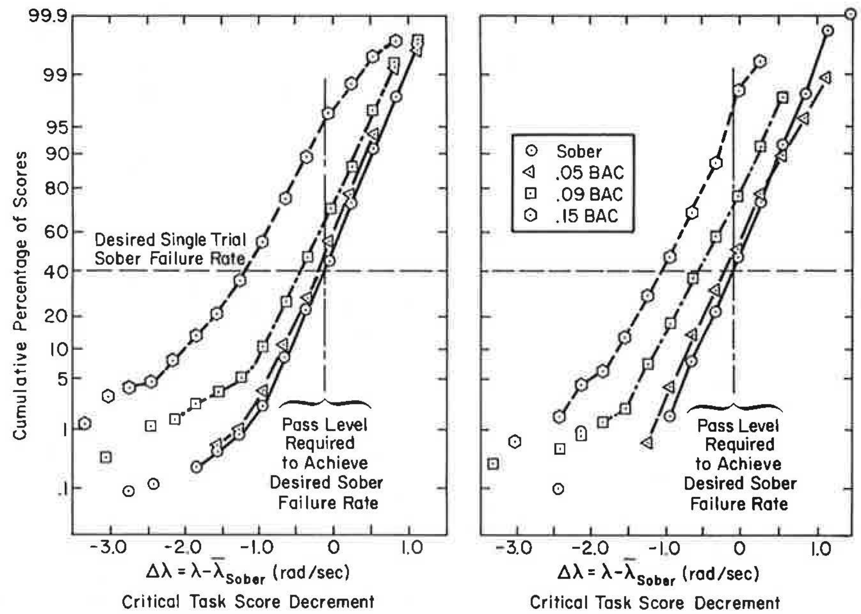
One of the most important aspects of this test is that it measures the impairment level of the operator regardless of the cause. Although blood alcohol concent (BAC) is an effective predictor of impaired driving ability, there are many other factors that may impair driving ability that BAC cannot address. Some of these impairing factors may only impair driving ability at certain times. For example, loss of sleep or stress may, alone, not affect the driver's ability, but when combined, may have devastating effects. As another example, an over-the-counter cold remedy, or a single beer may, alone, not impair the driver, but when combined, can have an effect greater than a BAC of 0.15 percent (one and one-half times the common legal limit for alcohol).

IMPAIRMENT DETECTION STRATEGY

Details of the development and optimization of the impairment detection strategy (IDS) have been described previously (15,18). The objective of the IDS is to maximize the chance of detecting operator impairment with a minimum number of CTT trials. This research developed a statistically based decision strategy to maximize test discriminability (i.e., low failure rate for normal operators and high failure rate for impaired operators). The IDS development and optimization strategy started with an analysis of the statistical properties of CTT performance (λ_c). Analysis of past data showed trial-to-trial and between-subject performance variability to be quite consistent across several studies (15,18) and a reliable effect of alcohol impairment was noted as illustrated in Figure 2. It was also found that subjects could be rapidly trained on the CTT but residual, long-term skill improvement would have to be accounted for.

Based on the statistical analysis of past data, several IDS requirements were established: (a) significant performance differences between operators require individualized pass criteria; (b) stable performance score variance and relatively independent trial-to-trial performance variability allow the use of simple multiple sampling strategies; and (c) long-term residual skill improvement would require procedures for sampling and periodically upgrading performance criteria.

The important statistical characteristics of CTT performance relative to IDS development can be illustrated with cumulative distribution functions as shown in Figure 3. The distributions are normalized and averaged across a large number of subjects and plotted on probability paper (a Gaussian distribution plots as a straight line). The data are normally distributed over a wide range, and the alcohol effect is clearly indicated. The basic requirement of the IDS is that sampled subject performance must exceed a preset pass level. Several sampling strat-



a) Data From Oates, 1975b *b) Data From Oates, 1975a*

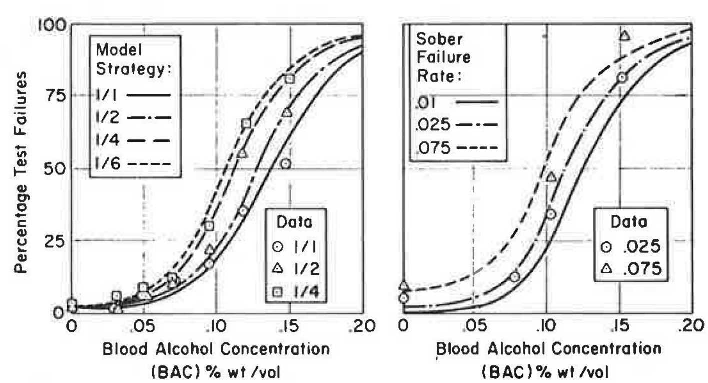
FIGURE 3 CTT differential score distributions averaged across 24 subjects in each experiment.

egies were analyzed and tested with past data bases (15,18) and, for various reasons, a "one-pass" out of several permitted attempts was selected. With this strategy, and assuming independent trials, the probability of failing the test is the single trial probability of failure raised to the power of the number of permitted attempts:

$$P_{fail}(\text{N trials}) = [P_{fail}(\text{single trial})]^N$$

This approach permits us to simply define the pass level given a subject's performance distribution and a desired probability of test failure when sober. For example, for a 2.5 percent failure probability given four attempts, the single trial probability must be approximately 40 percent [i.e., $(0.4)^4 \cong 0.025$]. Given this sober pass level as indicated in Figure 3, one can also derive the expected drunk failure rates [i.e., at BAC = 0.10, $(0.76)^4 \cong 0.35$, and at BAC = 0.15, $(0.96)^4 \cong 0.85$]. A statistical model based on this procedure was developed, and IDS model predictions of failure rates were compared with failure rates obtained with the IDS applied to past experimental data (15). The discriminability results are illustrated in Figure 4.

The preceding good agreement between model and data suggest that the detection strategy is well understood, and that an adequate procedure for establishing task performance pass levels has been established. In addition, the strategy and procedures embody two other desirable features: (a) the pass levels are near a subject's average or median performance level, which is stable and can be determined reliably; and (b) a subject's cumulative distribution function can be used to easily determine pass



a) Variation in Permitted Attempts at Constant Sober Failure Rate = .025

b) Variation in Sober Failure Rate for a One Pass in Four Attempts (1/4) Strategy

FIGURE 4 Impairment detection strategy comparison between model analysis and experimental data (strategies involve one pass in several attempts—1/N).

level, and also to upgrade the pass level to account for residual skill improvement.

LABORATORY VALIDATION EXPERIMENT

To validate the effectiveness of the CTT and IDS just described, an experiment was conducted that compared the CTT score with both BAC (in weight per volume) and driving performance in a driving simulator (15). Subjects were convicted drunk drivers obtained through the cooperation of the Los Angeles Municipal Courts. Twenty-four so-called "volunteers" were permitted to participate in the experiment as a condition of probation, and, in exchange, received a reduction in their court-sanctioned fine.

After being accepted, the subjects were required to participate in three 2-hr training sessions and three full-day experimental sessions. On the two drinking days, the subjects were dosed to 0.15 percent BAS (±0.01 percent). CTT trials were recorded at the peak BAC (0.15 percent) as well as at descending BACs of 0.10 and 0.075 percent. On one of the days, driving simulator data were obtained at BACs of 0.15 and 0.10 percent. On the other day, these data were collected at 0.15 and 0.075 percent. Each subject participated in one placebo and two drinking sessions. The subject population was divided into three groups matched for age, sex, and driving experience, and the order of occurrence of placebo session was different for each group.

Validation experiment results are summarized in Figure 5. Notice, first, that the discriminability data agree with the statistical model developed from past experimental studies. More importantly, analysis of simulator data shows a high correlation between simulator accidents and test failure. As shown in Figure 5, pre-drive CTT failures detected 81 percent of subsequent simulator accidents at a BAC of 0.15 (i.e., 81 percent of the accidents at 0.15 BAC were associated with CTT failures). These correlations between predicted and actual test performance show that it is now possible to both predict and verify vehicle operator impairment using a cybernetic test such as the CTT in combination with a suitable IDS.

Additional findings were also obtained on subject training procedures. CTT performance obviously has a strong motivational component. The validation experiment subjects were assigned by the traffic court and were not truly motivated volunteers. Several subjects exhibited a lackadaisical attitude during training, and were not encouraged by the positive reinforcement payments that were offered for good performance. In a subsequent training experiment (19), it was found that giving a time penalty (30-sec wait) for test failures was a much more effective way to deal with nonvolunteer subjects who were motivated mainly to minimize their time involvement.

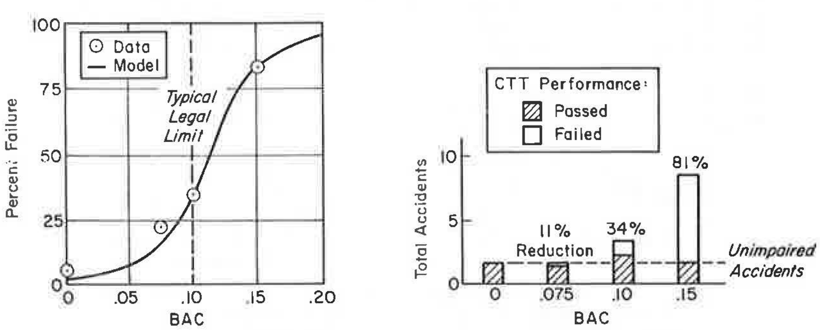
FIELD VALIDATION EXPERIMENT

The purpose of the field validation experiment was to demonstrate that a vehicle-mounted CTT-IDS could be assigned to convicted drunk drivers on a practical basis. This included selection and assignment by traffic courts and exclusive routine use by the recipients for a 6-month period. The vehicle-mounted test equipment, shown in Figure 6, combined the CTT-IDS into a system called the Drunk Driving Warning System (DDWS) and was installed in 10 1978 Chevrolet Nova automobiles. The subject had to pass the DDWS test in order to deactivate certain alarms: the car could be driven without passing the test but, in this case, the emergency flashers would operate and, if the car was driven over 10 mph, the horn would honk once per second. If the driver failed the test (four fail trials in succession), the computer required a 10-min wait before retesting was permitted.

Various countermeasures were incorporated into the DDWS to prevent cheating. These included sealing components and cables to prevent or reveal physical tampering, and requiring retesting if the driver left the driver's seat or opened his door after starting the test. An event recorder was also incorporated into DDWS to monitor the driver's use of DDWS and record instances of test failure and/or driving with alarms activated. Extensive usage data by time of day were obtained.

Two municipal court judges were willing to administer the DDWS as a sanction to convicted drunk drivers. The California law was temporarily modified to permit experimental evaluation of the DDWS sanction. Approval and/or cooperation was obtained from various state agencies (e.g., the Department of Motor Vehicles) in order to carry out the field test program. Nineteen drivers were subsequently assigned DDWS vehicles to be used exclusively over a 6-month period. Their licenses were restricted so that they could not legally drive any other vehicle. After initial training, the alarm system was activated and the subjects were required to check in at 2-week intervals. During the check-in sessions, the car and DDWS system were inspected, the data tape was removed, and the computer was analyzed. The subjects were debriefed and questioned about test failure episodes. (There was no penalty for admitting such instances during the test period.)

The design of the field test experiment was



a) CTT Impairment Discriminability, Data and Statistical Model Comparison

b) CTT Failure Detection of Simulator Accidents

FIGURE 5 Results from laboratory validation experiment (one-pass-in-four-attempts detection strategy, desired sober failure rate = 0.025).

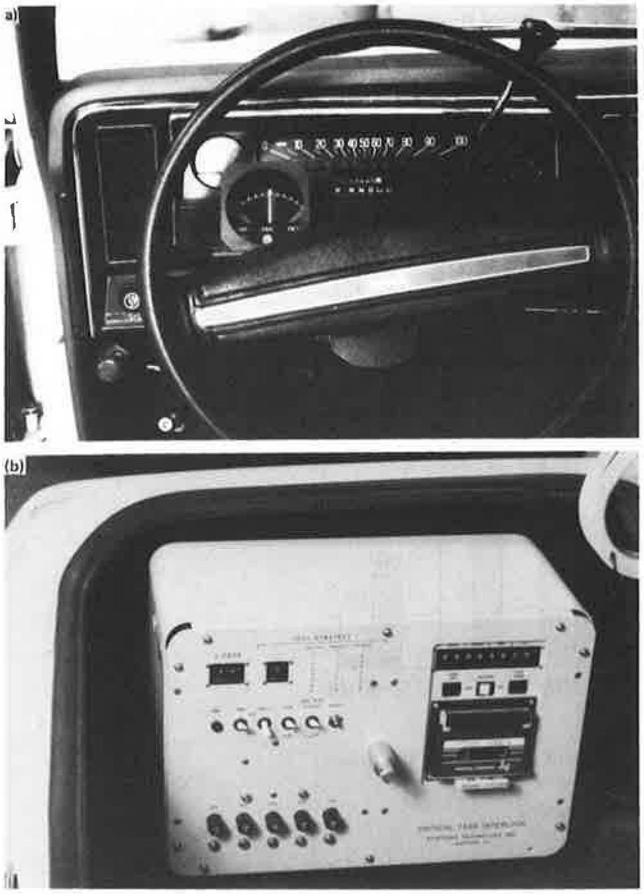


FIGURE 6 Vehicle-mounted field test apparatus (a) subject display and steering wheel control, and (b) trunk-mounted electronics and cassette data recorder.

divided into three major phases. The DDWS alarms were turned off during the initial and final 4-week periods (Phases I and III) and were activated during the middle 18-week period (Phase II). This design feature was incorporated to observe the influence of the DDWS system on driving patterns. Phases I and III were further subdivided into 2-week periods where the test was either active or inactive. This feature was included to see whether the requirement for taking the CTT test influenced driving patterns. Training on the CTT test took place during the second half of Phase I.

RESULTS

The overall results were derived from three basic data sources: (a) recorded data, which were retrieved and reviewed at the biweekly check-in sessions; (b) in-depth assessments developed during data reviews and debriefings at the biweekly check-ins; and (c) structured interview data obtained from subjects, colleagues, and relatives of subjects, court, and state agency personnel associated with the program, and others associated with the general drunk driving problem. Results from these three sources are described in the following paragraphs.

Recorded Data

Recorded data were analyzed to look for DDWS influence on driving patterns, subject performance, and the ability of DDWS to detect impaired drivers. Requiring the driver to take the CTT test with or without the DDWS alarms activated seemed to have little effect on day or night driving patterns (16). An analysis of test passes and failures was performed for check-in sessions at the beginning and end of Phase II (alarms on) and the end of Phase I and beginning of Phase III (alarms off). The purpose of this analysis was to determine whether having the alarms activated affected vehicle usage.

Data for test attempts as a function of time of day are shown in Figure 7. Chi-squared analysis showed the test attempt differences between alarms on and off to be marginally significant ($p = 0.038$). On a relative basis, the alarms-on versus alarms-off test attempts are small except for the early morning hours (12:00-4:00 a.m.). Time-of-day differences were ob- viously highly significant. Time-of-day interactions with test attempts and performance (pass/fail) were found to be significant while most weekday-versus-weekend interactions were found to be small or not significant (18). Thus, further analysis was restricted to time-of-day effects.

Failure rates for various time periods are shown in Figure 8. Daytime failure rates were about what was expected (i.e., ≅ 2.5 percent) based on the procedure used to set individualized CTT pass scores. Nighttime failure rates were three to seven times greater than this level, however, which is consistent with high incidence of drinking and driving during nighttime "recreational-social" periods versus daytime trips for commuting to and from work and running errands.

In-Depth Analysis

Because no objective data were available on subject BAC, the ability of DDWS to circumvent drinking-driving trips rests on circumstantial objective evidence such as is shown in Figure 8. Debriefing information was obtained on all test failures, however, and these data were combined with objective data as summarized in Table 1 to further classify test failure. Total test failures have been partitioned according to whether the driver was determined to be sober, impaired, or whether some equipment problem might have caused the failure (equipment malfunction episodes were experienced with several subjects).

Differential test scores (test score-pass level) were computed from the cassette-logged data, and when this score was greater than -0.4 (i.e., the test score was greater than a score 0.4 units below the pass level), the subject was assumed to be sober when the test was taken. This assumption was based on analysis of a statistical model for CTT scores and amounts to a 95 percent level of confidence that BAC was less than 0.05 percent weight per volume (18). In the case of subject 19, it was decided that his pass level in the beginning was set too high, so his total failures for $\Delta\lambda \geq -0.2$ were used. Problem failures were interpreted from the in-depth analysis, and the impaired failures were given by

$$F(\text{Impaired}) = F(\text{Total}) - F(\text{Sober}) - F(\text{Problem})$$

As noted in Table 1, even if the sober and problem failures are accounted for, there still remains a significant portion of impaired failures, with two subjects accounting for the majority of these. The DDWS alarms should deter the subject from driving, but as recorded by the data logger and indicated in Table 1, three subjects drove with the alarms activated.

Subjects 17 and 20 had isolated incidences where the car had to be moved a short distance. Subject 19

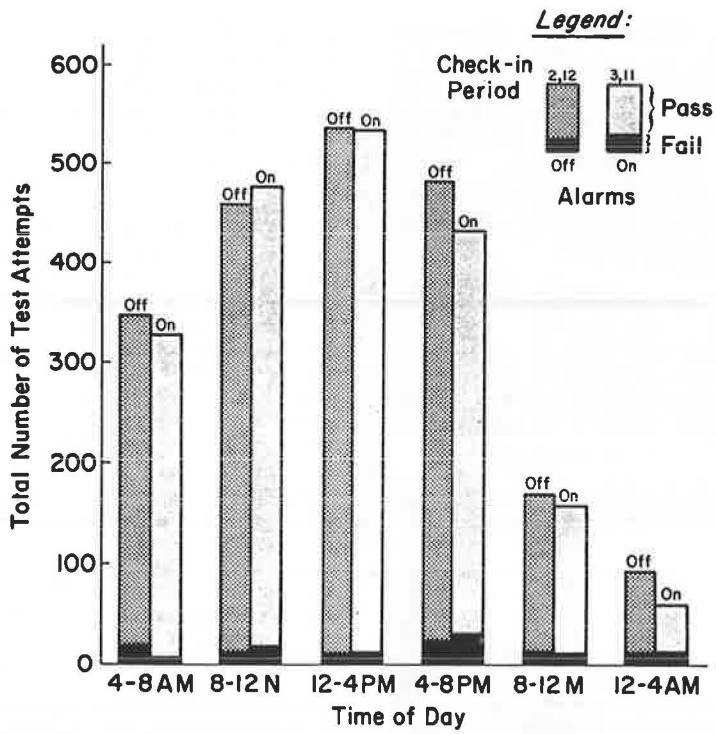


FIGURE 7 Effects of alarms on test attempts and performance (pass/fail) as a function of time of day.

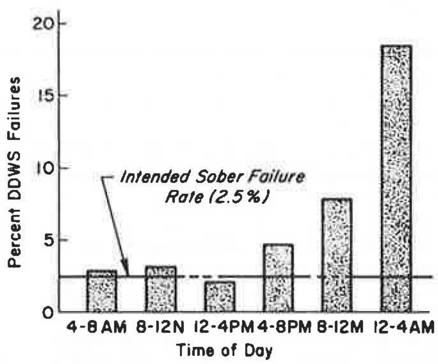


FIGURE 8 DDWS failure rate as a function of time of day.

TABLE 1 In-Depth Analysis of Test Failures

Subject No.	Test Failures: Total	Sober ($\Delta\lambda_p \geq -0.4$)	Problem	Impaired	Trips with Alarms
01	36	9	3	24	0
05	20	6	8	6	0
06	5	3	0	2	0
07	4	2	1	1	0
08	6	4	1	1	0
09	4	3	1	0	0
10	14	9	2	3	0
11	8	4	1	3	0
12	17	9	1	7	0
13	38	26	6	6	0
14	29	12	12	5	0
15	6	5	0	1	0
16	4	3	2	0	0
17	26	5	10	11	1
19	112	24[a]	8	81	5
20	13	12	0	1	1
22	9	4	2	3	0

[a] $\Delta\lambda_p \geq -0.2$.

actually admitted to occasionally driving his car without passing the test after drinking. This constituted a fairly serious violation of one of the conditions of probation, and the court was so notified. Subject 19 was cooperative, however, and it was recommended that he be permitted to remain in the program.

Debriefing Information Analysis

The municipal courts and the California Department of Motor Vehicles carried out their part in project support without serious problems. The courts do need an individual to take charge of subject screening, however, as was available through the West Los Angeles Municipal Court. Also, license restriction needs to be indicated on the front of the license to alert enforcement personnel and others (e.g., car rental agencies) of the DDWS user's restricted driving privilege. California is currently investigating this feature and may provide it in the near future.

Public acceptability for the DDWS concept has been quite good, once the objectives, approach, and background have been fairly presented. News media accounts of DDWS were fair and many times positive, although occasionally with some minor misinformation. Positive opinions have also been elicited by other individuals associated with the drunk driving problems, including relatives and colleagues of the DWI offenders employed here as subjects.

Finally, subject acceptance was quite good. No one found the DDWS to be a hardship, and most found it to be a desirable and effective sanction. Most subjects would choose DDWS rather than fines, license restriction or suspension, or jail.

CONCLUDING REMARKS

The data presented here and elsewhere (18) indicate that a DDWS-equipped vehicle can maintain good impaired driver discriminability in a field setting. As to whether subjects drive after test failure, in-depth analysis showed that only three subjects drove with the alarms on (a violation of probation that is recorded by the DDWS data logger). One subject was determined to have driven while impaired and, even in this case, there is some indication that the drive was made at low speed. Thus, test failure would appear to significantly deter driving-while-intoxicated trips.

The CTT/IDS could be used as a cybernetic screening device in other scenarios such as daily screening of commercial or government vehicle operators, industrial process or power plant operators, and so forth. Card/key systems could be used to permit a common device to be used by a number of individuals wherein the individual scores are updated in the card via a magnetic strip. Finally, the IDS could be used with other cybernetic tasks that might prove to be sensitive to other aspects of human operator impairment (20).

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Driver Inattention and Highway Safety

E. D. SUSSMAN, H. BISHOP, B. MADNICK, and R. WALTER

ABSTRACT

The Transportation Systems Center, in support of research carried out by the National Highway Traffic Safety Administration's Crash Avoidance Division, has reviewed research into driver attentional processes to assess the potential for the development of methods and techniques for reducing the number of accidents related to attentional lapses. Contained in this paper is a summary of the results of the review with regard to the (a) safety implications of inattention, (b) psychological and physiological indices of inattention, and (c) in-vehicle instrumentation for detecting inattention. Areas of research are suggested that could be valuable in the development of practical attention monitors for in-vehicle use.

The Transportation Systems Center, in support of research carried out by the National Highway Traffic Safety Administration's (NHTSA) Crash Avoidance Division, recently completed a review of driver attentional processes. A summary of the results of that review are contained in this paper.

Lapses in driver attention have been identified as a significant contributing factor in as many as 90 percent of traffic accidents. In light of this fact, an effort was conducted to determine the potential value of developing a system to monitor driver attention. This effort consisted of a review of the state of the art of research into driver attentional processes, analysis of the 1982 National Accident Sampling System (NASS) data, and investigation of the current technology available for sensing degradations in driver alertness. The material in this paper is abstracted from a report prepared for NHTSA's Crash Avoidance Division entitled, Potential for Driver Attention Monitoring System Development (1).

The status of research into driver attentional processes has remained fairly constant since Shinar et al. documented their review of the concepts of attention in 1978. More recent research has confirmed the general conclusions drawn by the studies reviewed by Shinar et al., as well as reiterating the complexity of driver attentional processes. It was apparent from reviewing the available data that combining indicators of the attentional state with indicators of the driving environment could significantly improve the accuracy of driver-attention monitoring.

NHTSA's accident data base is a valuable resource for estimating the impact of driver attention on highway safety. The 1982 NASS data were analyzed to develop hypotheses on the influence of driver inattention on traffic accidents. The 1982 data were selected because they represented the first file that emphasized driver-related factors in crash avoidance. The data showed that in accidents where an avoidance maneuver might have been of value, a large portion (37 percent) of the drivers involved took no action to avoid the collision. This supports the hypothesis that attentional lapses are a major factor in highway accidents. Another possibly large portion of drivers did not take action until it was too late to avoid the accident. It is suspected that driver inattention played a major role in these accidents as well.

Several devices have been developed over the years to monitor driver alertness and to stimulate the driver when a degradation in performance occurs because of inattention or drowsiness. A number of these devices are currently commercially available. These devices range from a simple head-droop alarm to a microprocessor-based monitor of steering wheel motion, driving-pattern, and time patterns fully integrated into an automobile system as original equipment. Both physiological and behavioral inattention indicators were investigated with respect to the technology of sensing the indicator and relative advantages and disadvantages of each as a practical monitor of inattention.

BACKGROUND

To a large extent, the safe operation of any system requiring direct human control depends on the level of attention that the human controller provides. In the case of motor vehicle operation, the driver must sample the driving environment, select the critical aspects of the environment, determine the proper response(s), make the response(s), and evaluate the outcome(s) of the response(s). To the extent that the driver does not sample the environment with sufficient frequency, does not select the appropriate stimuli, or does not respond in a timely manner, safety will be diminished.

Available driver inattention countermeasures include work-rest scheduling, educational campaigns, use of chemical stimulants, and the detection of degraded alertness (as inferred from changes in performance) through the use of sensor systems. In industrial and military settings, the alleviation of alertness-related safety problems generally is handled through the establishment and enforcement of duty schedules. The establishment and enforcement of work-rest schedules is not a practical countermeasure for dealing with the vast majority of road vehicle accidents because they involve either private automobiles or owner-operated trucks. Educational and public information campaigns range from defensive driving courses to public service announcements before national holidays. Perhaps the most popular countermeasure is the use of legal and illegal chemical stimulants (particularly caffeine) to improve alertness.

ATTENTIONAL PROBLEMS

As Zaidel, Paarlberg, and Shinar noted in their comprehensive review (2), lapses in driver attention can be assumed to be a significant contributory factor in traffic accidents. They cite estimates from 15 to 90 percent as the proportion of traffic accidents related to inattention. This great range can, to a large extent, be attributed to differences in definitions of attention-related problems.

For the purpose of examining the impact of such failures on driving safety, it is valuable to consider physical and psychological states that are likely to degrade alertness and to describe their impact on driving performance as follows:

1. Drowsiness: Except in cases where there is a known organic cause, such as narcolepsy, drowsiness can be attributed to a lack of sleep or a disturbance to the sleep-rest cycle (dysynchronosis). There are complex hypotheses that explain the need for periodic sleep and dreaming. These relate to the diurnal, hormonally regulated rhythms that cause the periodicity of sleep and the need for a reorganization of information acquired during waking hours, respectively. Whatever the causes of the need for sleep and concomitant dreaming, it is clear that "sleep deprivation leads to increased performance degradation as a result of an increase in the frequency of automatic periods of light sleep during enforced wakefulness and a heightening of the threshold of stimulation required to keep the individual from falling asleep" (3). It is the occurrence of the light microsleeps that is a problem in highway safety. During these microsleeps, the driver neither attends nor responds to the driving environment.

2. Physical fatigue: This can be a result of continued physical exertion or exposure to environmental stresses such as temperature and humidity extremes, excessive acoustic noise levels, and severe physical vibration. Physical fatigue is likely to result in distraction or an increased concern with internal stimuli and a concomitant decrease in attention to external stimuli. This change in focus from external to internal stimuli can be hypothesized to result in the driver missing critical signals. Further, fatigue can result in decreased response accuracy by the driver. This can cause a greater number of responses to be required to achieve a desired maneuver, which will further distract the driver from concentrating on external events. Physical fatigue is often a problem in military and industrial settings. It is less likely to be a problem for passenger car drivers than for the operators of heavy trucks who are often subjected to high noise and vibration levels.

3. Excess mental workload: Here, the driver has to many stimuli to attend to or too many responses to make in a limited amount of time. Skilled drivers learn to handle this situation by restricting their attention monitoring to the most critical inputs and meeting only the most critical control requirements. Less-skilled drivers may choose to monitor inappropriate inputs or to make noncritical responses. Some drivers may go into saturation and make no response, or they may freeze.

4. Intoxication due to alcohol, drugs, or other chemicals: Reductions in alertness are a direct or side effect of the use and/or abuse of a large number of substances. The exposure to pollutants, chief among them carbon monoxide, produces drowsiness, unconsciousness, and eventual death. The effects of the ingestion of illegal drugs and legal medications vary as widely as do their chemical formulae, ranging from depression and drowsiness through agitation to hallucination. Although alcohol abuse by motor vehicle operators is perhaps the single greatest cause of traumatic injury in the United States today, there is still considerable debate with regard to the particular behavioral changes caused by alcohol ingestion that result in dangerous driving practices.

5. Simple inattention: In this case, the driver either is not attending to any stimuli or is not attending to the proper external stimuli. This behavior can be described as daydreaming, woolgathering, or any of a number of colloquial terms. This inattention may be the result of any or all of the previously described problems, or many simply result from introspective behavior by the driver or a distraction of the driver. The operational result is that the driver makes a delayed response, an inappropriate response, or no response at all.

While the previously described conditions have a wide range of physiological concomitants, they have one particular behavioral similarity: in a nonalert state, the driver is less likely to respond in a fashion timely and appropriate to his or her environment than in the alert state.

In a laboratory setting with a controlled environment, the reduction in response frequency and appropriateness can be readily measured. The challenge is to discriminate accurately and reliably between changes in responses due to driver alertness and those changes imposed by driving conditions in the real world. Described in this paper is an attempt to assess the near-term feasibility of driver alertness measurement.

ACCIDENT STATISTICS

Accident Descriptions

To develop hypotheses about the impact of driver inattention on traffic accidents, data were obtained from the NASS Files. The 1982 NASS file was chosen because it was the first file to provide detailed information on the driver's role in traffic accidents. Data from a particular subset of accidents were selected to investigate inattention. These data came from reportable accidents where the vehicles involved were moving and the role of the drivers involved had been recorded. The following paragraphs contain descriptions on the factors used in analyzing the file.

Vehicle Factors

Vehicle factors are described as follows:

- Vehicle Role--Striking/Struck and Single-Vehicle Accidents: Striking and struck were extracted to eliminate vehicles involved in chain reaction accidents (both striking and struck). Driver attention clearly is more important with regard to the role of the driver in the striking vehicle. However, in some cases, if the driver of the struck vehicle properly responds in a preaccident situation, the accident can be avoided or the severity of impact reduced. To reduce the ambiguity with regard to the role of the struck vehicle's driver, only cases where the vehicles were in motion were considered (see Vehicle Speed). Based on the NASS definitions of vehicle role, single-vehicle accidents are included in the striking/struck categories. Both a vehicle striking another vehicle and a vehicle striking a roadside object are classified as striking vehicles. A struck vehicle in a single-vehicle accident would have been hit by something other than another vehicle, such as a pedestrian or some form of debris.
- Vehicle Speed: Only cases where vehicles had speeds greater than 0.5 mph before the accident were considered because it was assumed that driver re-

sponse was likely to be critical only when his or her vehicle was moving.

Driver Factors

The following driver factors are described:

- Attempted Avoidance Maneuver: Two levels were examined: cases where no avoidance maneuver occurred and cases where any avoidance maneuver occurred.
- Driver Drowsy: This driver factor reflects cases where the driver's being drowsy, asleep, or fatigued was considered a cause of the accident.
- Driver Drugs--Medication: This factor reflects cases where the use of legal drugs was considered to be the cause of the accident.
- Driver Other Drugs: In these accidents, the cause was attributed to the driver's use of illegal drugs.
- Driver Inattention: In these accidents, the cause was attributed to the driver's lack of attention.
- Alcohol Abuse: In these cases, the measured blood alcohol content (BAC) of the driver was in excess of 0.07 percent.
- Age of Driver: Drivers were grouped by age from 20 to 70 years old in 5-year intervals.

Accident Factors

Accident factors are described as follows:

- Land Use: Land use groups the accidents in terms of urban or rural sites.
- Time Period: The day was divided into five time periods: early morning (accidents that occurred between the hours of midnight and 5:59 a.m.), the morning rush hour (all accidents that occurred between 6:00 a.m. and 9:59 a.m.), midday (10:00 a.m. to 3:59 p.m.), the evening rush hour (4:00 p.m. to 6:59 p.m.), and evening (7:00 p.m. to midnight).
- Road Alignment: The data were grouped into accidents that occurred on curved and straight sections of roadway.
- Number of Occupants: The data were examined to determine the influence of the presence of passengers in a vehicle (greater than one) on the accident. Vehicles having the driver as the only occupant were designated as occupant equal to one.
- Day of Week: The week was divided into weekdays (Monday through Friday) and weekends.

The NASS file provides a number of methods for estimating the role of attentional factors in crash avoidance. For the purposes of this document, the NASS file output was structured to examine the relationship between the previously listed driver factors and crash frequency. Although the report this paper is abstracted from deals with all of the factors listed, perhaps the most suggestive information comes from considering the vehicle role.

1982 NASS DATA

Failure to Make a Precollision Response

The broad operational definition of driver inattention used in this paper is as follows: the attentional state where the driver fails to respond to a critical situation. Figure 1 shows the frequency of all collision accidents where the role of the vehicle was known to be either striking or struck (vehicles whose roles were unknown or were involved in chain reaction collisions were not included) and the vehicles were in motion. In the 1982 NASS file, there are 11,868 vehicles involved in accidents that meet these criteria. In these accidents

- 2,665 (or 22.5 percent) were striking vehicles whose driver took no avoidance action before the collision;
- 1,838 (or 15.5 percent) were struck vehicles whose driver took no avoidance action before the collision;
- 5,916 (or 49.8 percent) were striking vehicles whose driver took avoidance action before the collision; and
- 1,449 (or 12.2 percent) were struck vehicles whose drivers took avoidance action before the collision.

Drowsiness

Figure 2 represents breakdowns of the frequency of all collision accidents where the driver was judged to be drowsy, the role of the vehicle was known to be either striking or struck (vehicles whose roles were unknown or were involved in chain reaction collisions were not included), and the vehicle was in motion. In the 1982 NASS file, 176 (or more than 1 percent) of all collisions involved vehicles in accidents that met these criteria. In these accidents

- 104 (or 59.1 percent) were striking vehicles whose driver took no avoidance action before the collision;

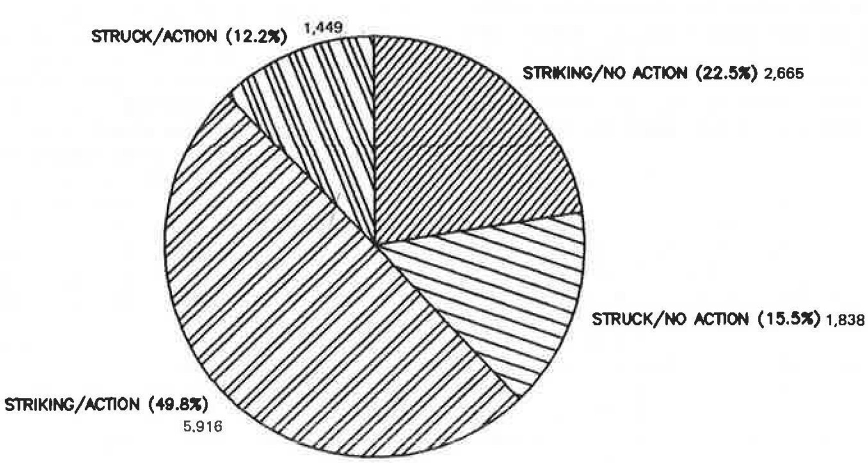

FIGURE 1 Driver responses in all collision accidents.

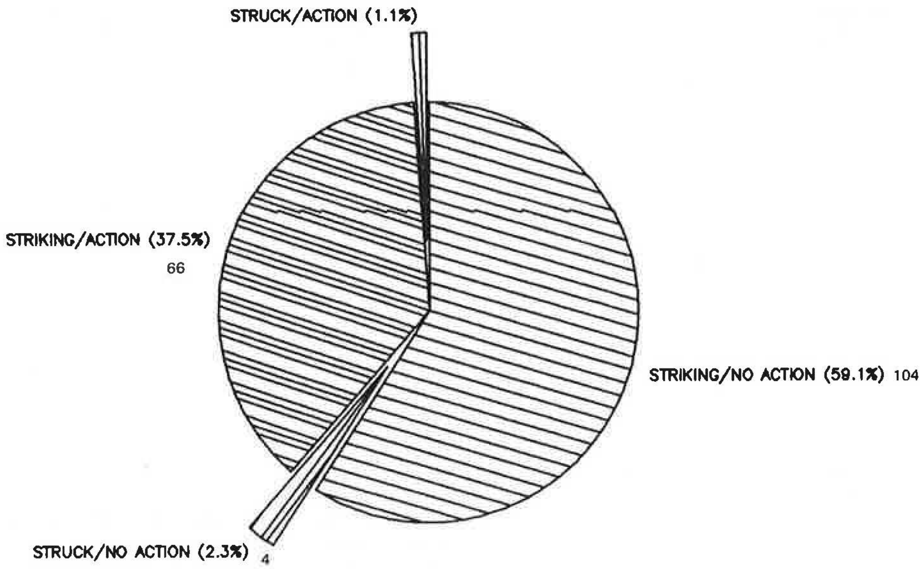

FIGURE 2 Accidents attributable to drowsiness.

- 4 (or 2.3 percent) were struck vehicles whose driver took no avoidance action before the collision;
- 66 (or 37.5 percent) were striking vehicles whose driver took avoidance action before the collision; and
- 2 (or less than 1.1 percent) were struck vehicles whose driver took avoidance action before the collision.

Drunkenness

Figure 3 gives breakdowns of the frequency of all collision accidents where the driver had a BAC in excess of 0.07 percent, the role of the vehicle was known to be either striking or struck (vehicles whose roles were unknown or were involved in chain reaction collisions were not included), and the vehicle was in motion. In the 1982 NASS file, 376 (or 3 percent) of all collision-involved vehicles in accidents meet these criteria. In these accidents

- 157 (or 41.8 percent) were striking vehicles whose driver took no avoidance action before the collision;
- 11 (or 2.9 percent) were struck vehicles whose driver took no avoidance action before collision;
- 195 (or 51.9 percent) were striking vehicles whose driver took avoidance action before the collision; and
- 13 (or 3.5 percent) were struck vehicles whose driver took avoidance action before the collision.

Medication--Legal and Illegal

Drivers involved in accidents meeting the previously mentioned collision criteria who were found to have

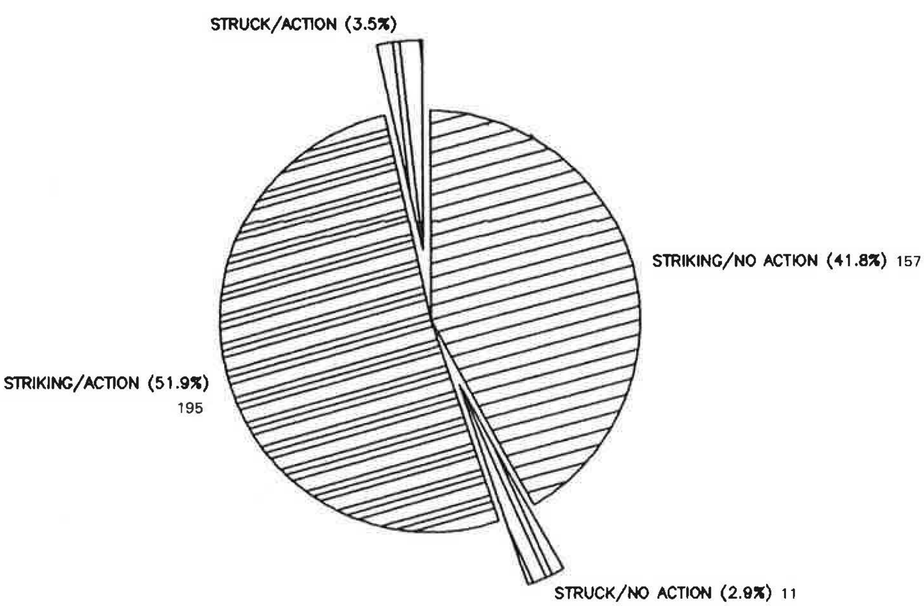

FIGURE 3 Accidents attributable to drunk drivers.

TABLE 1 Percentage of Drivers Making No Precollision Maneuver

Driver Age	Striking (%)	Struck (%)
Under 20	24	47
20-24	30	54
25-29	29	52
30-34	33	58
35-39	29	53
40-44	33	57
45-49	37	61
50-54	36	57
55-59	35	60
60-64	39	58
65-69	43	64
Over 70	52	74

used legal or illegal drugs before the collision, respectively, represent less than 0.1 percent of the cases meeting the collision definition.

Driver Age

Table 1 and Figure 4 depict driver responses in accidents attributable to inattention versus age. The data indicate that younger drivers were more inclined to make avoidance maneuvers than older drivers. The relationship between failure to respond in a collision-type accident and age appears to be linear. As would be expected, the number of cases in which the driver fails to respond is greater in accidents in which the driver's vehicle is struck than when it is the striking vehicle.

Time of Day

Table 2 gives a distribution of accidents due to inattention by time of day. Between the hours of 6:00 a.m. and 4:00 p.m. (morning rush hour to midday), a higher percentage of drivers took no action to avoid

TABLE 2 Accidents Attributable to Inattention (1982 NASS)

	Avoidance Action		No Avoidance Action	
Time of Day	Total	Percent	Total	Percent
Morning rush hour	68	13	78	21
Midday	150	30	127	34
Evening rush hour	91	18	59	16
Evening	114	23	68	18
Early morning	81	16	40	11

Note: Data are for 946 of 11,868 accident cases.

an accident. After 4:00 p.m., drivers were more inclined to attempt an avoidance action.

SUMMARY

Thus, in all collision accidents in which the vehicles were under way and a driver response conceivably might have avoided the collision or lessened the severity of the collision (11,868 accidents), the NASS investigators found that

- Eight percent of the cases were specifically related to the driver being inattentive;
- One percent were related to the driver being drowsy;
- Three percent of the drivers were drunk;
- Less than 0.15 percent were attributable to the use of legal or illegal drugs;
- Thirty seven percent of the drivers made no precrash response of any kind; and
- The frequency of precrash response decreases as a function of driver age.

INDICATORS OF INATTENTION

Indicators of inattention have been extensively studied, including such physiological measures as

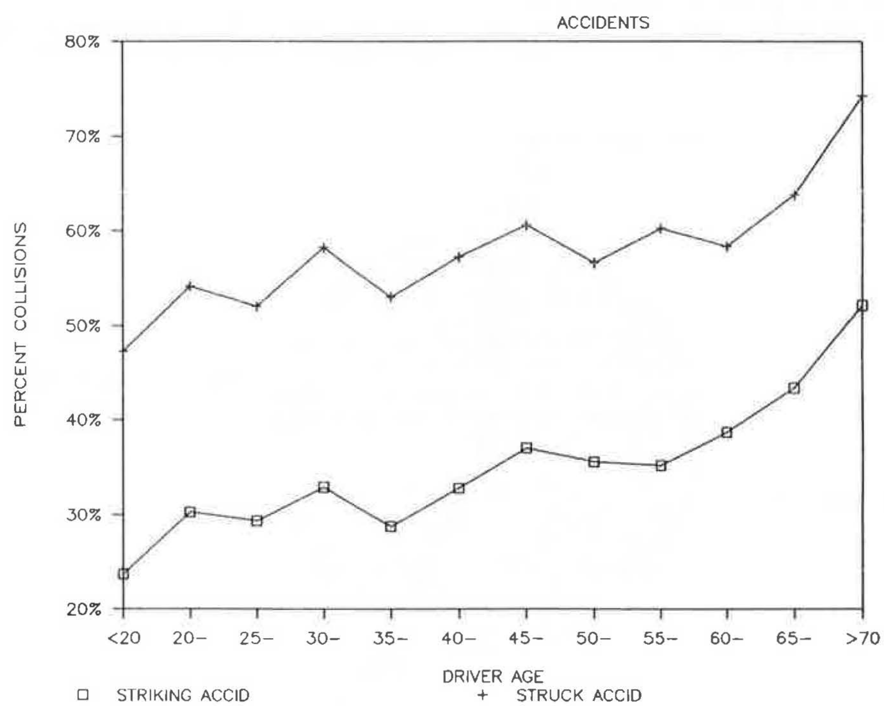

FIGURE 4 Percentage of drivers not making avoidance manuever in collision accidents.

TABLE 3 Physiological Indicators of Driver Attention

Indicator	Sensor	Measurement Dimension	Active[a] or Passive	Obtrusive[b] or Remote	Advantages	Disadvantages
Heart rate and variability (EKG)	Electrode or transducer	Voltage or pressure	P	O	Easy to monitor. Could be made remote by incorporation into steering wheel. Easy to interpret.	May require detailed spectral analysis. Individual variations are large.
Brain electrical activity (EEG)	Electrode	Voltage amplitude and frequency	P	O	Established relationship to fatigue and drowsiness.	Difficult to monitor or interpret. No remote sensing possible in the near term.
Skin conductance and electrodermal response (EDR)	Electrode	Voltage resistivity	P	O	Could be made remote by incorporation into steering wheel.	Individual variations in galvanic skin response are large. Relationship to inattention is not well established.
Muscle electrical activity	Electrode	Voltage amplitude and frequency	P	O	Relatively easy to monitor.	Relationship to inattention is weak. Remote monitoring is not possible in near term.
Body activity	Observer or switches	No. of movements State change frequency	P	R		Requires observer. No established correlation to inattention.
Respiratory pattern	Transducer	Frequency	P	O		Difficult to monitor. Correlation with vigilance is inconsistent.
Critical flicker frequency	Self-assessed	Null frequency	A	R	Easy to administer. Could be built into vehicle dashboard.	Driver would have to stop vehicle to administer. Weak correlation with fatigue.
Head nod angle	Switch	State change	P	O	Cheap, commercially available.	Measures last stage of drowsiness.

[a]"Active" (A) requires activity on the part of the driver. "Passive" (P) does not.
[b]"Obtrusive" (O) requires physical attachment to the driver. "Remote" (R) does not.

EKG, EEG, pulse and heart rates, and eye blinking. Behavioral indicators would include looking patterns, driver steering wheel use, accelerator and brake applications, lane drift, and closure rate. The physiological indices reviewed are given in Table 3 and the behavioral indices are given in Table 4. Although a number of indicators have potential utility for use in an inattention detection system, they tend to be ambiguous and unreliable when taken singly. These indicators are reviewed in detail in the previously mentioned report.

COMPLEX PERFORMANCE SIGNATURES

In response to this problem, a number of investigators have attempted to define combinations of indicators that would be more useful than single indicators alone. Some examples of recent efforts to develop complex performance signatures are described briefly in the following sections. For purposes of organization, they have been considered in two groups. The categories are chosen for convenience, and primarily imply a difference in perspective and

TABLE 4 Behavioral Indicators of Driver Attention

Indicator	Sensor	Measurement Dimension	Active[a] or Passive	Obtrusive[b] or Remote	Advantages	Disadvantages
Steering wheel reversals	Potentiometer, optical or magnetic transducer	Rate and angle	P	R	Easy to monitor. Studied extensively. Commercially available.	Affected by vehicle/driving environment. Individual variations.
Accelerator pedal movement	Linear potentiometer pressure transducer	Rate and amplitude	P	R	Easy to monitor.	No established relationship to attention. Individual variations.
Brake pedal movements	Linear potentiometer, pressure transducer	Rate and pressure	P	R	Easy to monitor.	No established relationship to attention. Individual variations.
Vehicle position (longitudinal, lateral, and heading)	Observer, sensitive guidance system, roadside edge monitor, radiation detector	Frequency, amplitude and angle, relative distance	P	R	Correlated with alcohol and drug use.	Difficult to monitor. Complex interactions.
Looking behavior	Observer, TV monitor, oculometer	Eye position and fixation frequency, pattern and duration	P	O or R	Correlated to all dimensions of attention. Can be made remote.	Interpretation difficult. Not useful in real time.
Blink rate	As above	Rate and duration	P	O or R	Can be measured remotely.	Weakly correlated with attention.
Secondary tasks	Many variations, usually tracking		A	R	Can be a simple device.	Distracts from main task.

[a]"Active" (A) requires activity on the part of the driver. "Passive" (P) does not.
[b]"Obtrusive" (O) requires physical attachment to the driver. "Remote" (R) does not.

assumed starting points of the investigators. The studies included in the first group are characterized by the use of multivariate statistical techniques to analyze and combine measures on selected variables. These measures are used to develop complex signatures or ad hoc models to assign a driver to a given behavioral group. The studies included in the second group, in comparison, are characterized by the assumption of some prior model of the driver. Statistical techniques may be used to determine parameter values or changes that may be used to categorize a driver.

STATISTICAL PROCESSING

A number of investigators have attempted to use multivariate statistical techniques to identify combinations of measures with greater discriminatory power than univariate indicators. In most cases, the focus of the effort has been on problems other than attentional performance; however, the approach has been fruitful, as shown in the following examples.

Lemke (4) used factor analysis and canonical correlation to establish multivariate relationships between changes in EEG patterns and changes in driver control activity during long periods of driving in a simulator and on the road. A more popular approach, however, has been to use discriminant function analysis. Hagen (5) derived discriminant function vectors using variables derived from four basic measures on subjects driving a point light source simulator. He found mean accelerator reversal rate, mean speed, lateral position error, and accelerator variability made the largest contributions to vectors discriminating between male and female subjects. Using this approach, he was able to develop vectors that discriminated between a number of groups including, for example, sex/violation, sex/accidents, sex/driving experience, and sex/risk taking.

Wilson and Greensmith (6) also used multivariate discriminant analysis to develop combinations of driving performance scores of males and females during 40 to 50 min of on-road driving. They found that combinations of seven variables were useful for discriminating between males and females. These were: number of speed changes, number of fine- and coarse-steering reversals (less than 2 degrees and greater than 20 degrees, respectively), moderate (0.15g) and strong (0.3g) lateral acceleration for a period of 1 sec or more, accelerator pedal activity, and clear road speed.

Attwood (7) obtained five measures of driving performance during 70-mi trips driven by experienced and inexperienced drivers. He found that no single variable was useful for discrimination between the groups. He derived 71 variables from the five base measures, and using multivariate discriminant analysis, he was able to develop a number of combinations that discriminated between the driver groups. For example, a driver's group could be predicted with a combination of scores on (mean lateral position) + (minimum lateral position), or a more complex combination of scores on (lateral position standard deviation) + (mean lateral position) (lateral position standard deviation) + (steering wheel reversals) + (accelerator pedal reversals).

Attwood et al. (8) used a similar approach to the development of a linear discriminant function that could be used to identify sober and intoxicated drivers. In another study, Attwood and Scott (9) applied this approach to the detection of sleepy drivers. In this latter experiment, they obtained behavioral and vehicle measures during two 3-hr driving periods separated by 21 hr of maintained wakefulness. By using these scores, they developed linear discriminant functions that could be used to identify drivers in the first and second driving periods. The smallest n-variable function was based only on measures of vehicle lateral position and steering wheel activity. It was expressed as

$$D(30) = 256\ V(1) - 159\ V(2) - 1.4\ V(3)$$

where V(1) and V(2) are the mean and maximum vehicle lane position, respectively, and V(3) is the steering wheel reversal rate in the range between 1.0 and 1.5 degrees. For longer sampling periods of 45 or 70 sec, the best functions included lane position and accelerator pedal activity rather than steering wheel activity. The function D(30) was applied to the performance scores obtained during a second set of 3-hr driving periods for one driver on one task. The power of the simple function for assigning the driver to the drowsy class, although limited, was reasonably good and demonstrated the potential utility of the approach.

FORMAL MODEL-BASED SIGNATURES

In recent years, there has been considerable interest and success in the development and application of general operator/vehicle models. Most work has used either the now classic quasi-linear, describing-function representation or the more recent optimal control, state space representation. Recent and accessible reviews of these developments are presented, for example, by Allen (10), McRuer et al. (11), Reid (12), and Rouse and Gopher (13). Although the optimal control, state-space approach eventually may prove to be of greatest value for describing complex, multivariate operator-system behavior, the quasi-linear describing function models are currently the most well-developed.

A number of simulator and on-road studies have been conducted in recent years to evaluate model and parameter requirements, and changes for different driving situations. For example, Donges (14) studied straight and curved road driving, Reid et al. (15) studied obstacle avoidance maneuvers, Allen (16) studied driver adaptive behavior, and Smiley et al (17) studied changes with driving experience.

In some recent studies, changes in the values of parameters of models have been used as indicators of changes in operator attentional state. Most of the studies have focused on changes associated with conditions requiring changes in the allocation of attention.

In studies of simple tracking behavior, interest has commonly focused on the parameters of gain, effective delay, lead-lag adjustment, and remnant. As Wickens and Gopher (18) indicated, open-loop gain is attenuated, lead is decreased, and/or remnant is increased with diversion of the operator's attention. These authors also observed an increase in the number of holds (no tracking response) related to the addition of secondary tasks and changes in both gain and power at low and high frequencies related to changes in primary and secondary task priorities.

The results of a driving simulator study by Allen et al. (19) generally confirm the results of the tracking test studies. In this study, the effects of changed attentional state related to the imposition of a secondary visual detection task and those related to the effects of driver BAC were examined in the framework of a quasi-linear, describing-function model. The effects of task loading and BAC were similar in that both resulted in reduced gain, particularly at low frequencies; increased remnant;

increased steering wheel activity; and increased heading and lateral position errors. There were also differences in the effects of the two types of conditions. Phase margin was not affected by driver BAC, but was increased with the addition of the secondary task. Crossover frequency, on the other hand, was not affected by the additional task loading, but decreased with increased BAC. Holds (no tracking response) on steering behavior were noted with intoxicated drivers during the visual response period, but were not observed with sober drivers.

Driver-vehicle models appear to provide an excellent means for expressing complex signatures necessary as a basis for an inattention detection system. Changes in the values and relations of variables and parameters of both ad hoc and formal models have been shown to be related to changes in driver physiological and psychological states and task demands. Research such as that of Attwood and Scott suggests the possibility of developing relatively simple, useful, ad hoc models with the use of multivariate analytical techniques. This approach provides flexibility in the choice of measures to be used, but the resultant models provide little guidance for the selection of measures or derived variables to establish or improve their discriminative power. Formal models, such as those used by Allen et al. (19) provide a fairly well-known and applied conceptual framework, but may be both more restrictive and demanding with respect to the measures that may and must be used. The possible requirement for input data to establish such model parameters as crossover frequency or phase margin, for example, may limit the use of formal models to research settings. Further research is necessary, however, to establish the minimum nonperformance input data for either type of model, technical means of providing this data, and the possibility of using predictive techniques to calculate probable input on the basis of driver and vehicle performance measurements.

DRIVER ALERTNESS MONITORS

The report reviewed the state of the art in driver alertness monitors. Currently, there are a limited number of such devices commercially available. These range from the unsophisticated head-droop alarm to the microprocessor-based monitor of steering-wheel driving pattern/driving-time patterns that is available in Japan on Nissan's Bluebird line of vehicles. (The monitors reviewed in the report are given in Table 5.)

Although not directly related to driver attention per se, the status of systems related to the vehicle and its environment were considered. These include radar warning and braking systems, navigational aids, roadside monitors, and automated highway systems. These systems could be considered as part of a multivariate approach to developing a driver alertness monitor.

The state of the art in automotive electronics was briefly reviewed in the report. The practical utilization of any of the aforementioned devices depends, to a large extent, on the development of sophisticated electronics for sensing, data handling, and analysis.

CONCLUSIONS

The material reviewed in the report suggests the following:

Accident Data

The fact that a large portion (37 percent) of drivers involved in automobile crashes, as reported in the 1982 NASS file, took no action to avoid the collision suggests that attentional lapses are a major factor in the causation of highway accidents and that these

TABLE 5 Driver Alertness Monitors

Monitor System	Sensor	Measurement Dimension	Active[a] or Passive	Obtrusive[b] or Remote	Advantages	Disadvantages	Availability	Cost ($)
Reli "Stay-A-Wake"	Optical transducer	Steering rate	A	R	Alerts driver when steering wheel movement rate drops below a given rate.	Standard steering movement rate must be set by driver. System effectiveness can be defeated.	Available from the manufacturer.	170
	Voltage	Vehicle speed	A	R	Will sound an alarm when vehicle reaches or exceeds a set speed.	Speed at which alarm sounds is set by driver.		
Slarner "Driver Alert Warning Device"	Switch	State change	A	O	Sounds an alarm when driver's head droops.	Warning does not occur until the driver is asleep.	Available from AAA.	33
Safex "Drive Alert"	Switch	State change	A	O	Sounds an alarm when driver's head droops.	Warning does not occur until the driver is asleep.	No longer available.	–
Nissan "Safety Drive Advisor"	Optical/velocity sensor	Rate and frequency	P	R	Monitors and records driver's initial steering reversal rate and alerts the driver if steering reversal rate differs from this standard.	Little detail of operational principle is known to date.	Available on Nissan Bluebird models. Not imported into USA.	85 (approx.)
	Electronic clock	Elapsed driving time	P	R	Alerts driver to take periodic breaks. Interval between signals is decreased by activation of headlights or windshield wipers.			
Life Technology/Ford "Owl"	Optical sensor	Rate	P	R	Monitors and records driver's initial steering reversal rate and alerts the driver if steering reversal rate differs from this standard.	Standard steering reversal rate can be adjusted by driver. System effectiveness can be defeated.	No longer available.	–

[a] "Active" (A) requires activity on the part of the driver. "Passive" (P) does not.
[b] "Obtrusive" (O) requires physical attachment to the driver. "Remote" (R) does not.

attentional lapses probably become a more important factor as a driver's age increases.

Research Findings

Changes in performance associated with task duration or drowsiness include: (a) a reduction in the frequency of control responses, (b) periodic "blockage" of all responses, (c) an increase in the amplitude of responses, and (d) an increase in the variability of the responses.

In controlled experiments, averaging across subjects who are exposed to the same conditions, there are reliable changes in performance that are monotonically related to attentional state.

Examination of the performance of the individuals in these studies indicates that while performance of selected tasks decreases with degraded attention, the relationship between the changes in performance and the attentional state varies significantly between the subjects.

The use of multiple performance indices will enhance the discriminative power of the attentional discrimination system. Although performance changes can reliably reflect modifications in attentional state, the most difficult problem in detecting degraded alertness will be to discriminate the effects of these changes from those imposed by the driving environment.

Driver Alertness Systems

Proprietary alertness indicators fall into two functional classes: those that evaluate performance and those that evaluate the physical or physiological state of the subject.

Indicators that are based on physiological or physical concomitants of attention are likely to be too cumbersome to achieve widespread use by private vehicle operators. Indicators that are based on the performance of an artificially constructed secondary task are likely to be distracting to the driver and, therefore, potentially hazardous. However, it may be possible to use performance measurements on noncritical tasks that are normally required, such as instrument scanning, as an index of alertness.

A driver attention indicator, regardless of its behavior, must be able to learn the shape of the normal performance curves that are particular to the individual driver. Then, it must be able to sense deviations from this norm that are not the result of changes in the environment and that provide warning of changes in alertness.

Of the proprietary devices reviewed, only one system is currently installed on production passenger vehicles in Japan. This system is based on a multivariate analysis approach and learns the patterns of driving performance of the individual driver, and represents a potentially promising approach.

The existing electronic systems and the nearterm projected advancements lead to the conclusion that electronics will soon be available to reliably track and analyze any practical driver alertness monitoring system.

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Estimating Highway Speed Distributions From a Moving Vehicle

JON D. FRICKER and HUEL-SHENG TSAY

ABSTRACT

The question of how to develop a distribution of speeds for vehicles passing and being passed by an observer car in the vehicle stream has attracted the interest of several mathematicians, but their published work has not gone beyond the theoretical stage. In practice, the theoretical expressions that have been developed do not permit the construction of an accurate speed distribution from actual data gathered from an observer car. The standard deviation of the distributions they construct are accurate, but their inability to process a few discrete data points causes errors in estimating the mean speed of the traffic stream. An observer car was operated over 817.9 mi of Interstate highway, gathering actual data for use in this study. A simulation program was written to help test an empirical method for constructing a speed distribution. The simulation revealed that the empirical method predicted the mean speed well, but estimated the standard deviation poorly. Furthermore, it illustrated why these inaccuracies resulted. Finally, a practical method was produced by which anyone can determine good estimates of both the mean and standard deviation of the speed distribution without special equipment.

In order to avoid losing certain federal-aid highway funds or to qualify for incentive grants, each state must compile annual speed compliance data. If more than 30 percent of the vehicles on a representative sample of highways in a state exceed 55 mph, that state may have 10 percent of its federal-aid highway funds withheld. If fewer than 20 percent exceed 55 mph, the state can claim an incentive grant (1). Often, as one is driving on an Interstate highway, it is difficult to believe that sufficient compliance is actually taking place. This paper presents a practical method of approximating, not only the mean speed of traffic, but the distribution of speeds in the stream of traffic surrounding a vehicle driven by an individual who is curious about speed compliance levels on a given highway section. This method describes the speed of vehicles throughout the traffic stream, not just at isolated speed monitoring stations.

A THEORETICAL BASIS FOR THE MODEL

A Mathematical Model

The authors are interested in the amount of accurate, useful information an individual in traffic can easily collect. (This person's vehicle shall be called the "observer car" in this paper.) What information must be collected or inferred in order to adequately describe the distribution of vehicle speeds? One way to answer this question is to build a mathematical representation of the traffic stream and the observer car's relationship to other vehicles in it. Employing a mathematical model usually requires the adoption of simplifying assumptions such as

1. Each driver in the traffic stream chooses a speed, v, and drives constantly at this speed.
2. If the observer car approaches a slower vehicle ahead of it, the observer car overtakes it without delay (i.e., there is no interaction between cars).
3. The traffic has reached "steady state."
4. Vehicles entering the highway follow a homogeneous Poisson process.

The following parameter definitions pertain to Equations 1-5:

- q = the flow of vehicles past a point on the highway (vehicles per hr);
- v_o = the speed of the observer vehicle;
- $F(v)$ = the probability that the speed of a vehicle selected at random passing a certain point on the highway is smaller than v. $F(v) = Pr(V \leq v)$. The random variables V are independently and identically distributed;
- $\lambda^+(v_o)$ = the number of vehicles overtaken by the observer vehicle (vehicles per hr); and
- $\lambda^-(v_o)$ = the number of vehicles that overtake the observer vehicle (vehhicles per hr).

From References 2 and 3, the following equations can be assembled:

$$\lambda^+(v_o) = q \int_0^{v_o} [(v_o - v)/v]\, dF(v) \qquad (1)$$

$$\lambda^-(v_o) = q \int_{v_o}^{\infty} [(v - v_o)/v]\, dF(v) \qquad (2)$$

From (1)

$$\lambda^+(v_o) = qv_o \int_0^{v_o} F(v) dv/v^2 \qquad (3)$$

Then

$$F(v_o) = 1/q\{[v_o\, d\lambda^+(v_o)]/dv_o\} - \lambda^+(v_o) \qquad (4)$$

Equation 3 shows that $\lambda^+(v_o)$ is an increasing function of v. For specified values of the parameters, Equation 4 estimates the ratio of the number of cars the observer car will pass to the number it will observe. Thus, if a driver travels for sufficiently long periods of time, periodically assumes different (but constant) speeds, and counts the number of cars overtaken (or that overtake him), the speed distribution and the traffic flow can be estimated (2,3). To use Equation 4, the difference between the number of vehicles overtaken by the observer car at speeds $v^1{}_o$ and $v^2{}_o$ needs to be determined. If the number of cars overtaken at speeds $v^1{}_o$ and $v^2{}_o$ are $\lambda^+(v^1{}_o)$, and $\lambda^+(v^2{}_o)$, respectively, then Equation 4 can be used in the following discrete form:

$$F(v^2{}_o) = 1/q\ \{v^2{}_o[\lambda^+(v^2{}_o) - \lambda^+(v^1{}_o)]/(v^2{}_o - v^1{}_o)\} - \lambda^+(v^2{}_o) \qquad (5)$$

For example, if the traffic flow (q) is 750 vehicles per hr, the observer car passes 15 vehicles while moving at 57.6 mph, and passes none at 52.8 mph, Equation 5 becomes

$$F(57.6) = 1/750[57.6(15 - 0)/(57.6 - 52.8)] - 15 = 0.22,$$

where 52.8 is the estimated speed of the slowest vehicle on the highway section of interest. Repeating this equation for four higher speeds (as shown in the following calculations) allows for creation of the plot in Figure 1.

$$F(61.4) = 1/750\ [61.4(29 - 15)/(61.4 - 57.6)] - 29 = 0.263$$

$$F(62.4) = 1/750\ [62.4(38 - 29)/(62.4 - 61.4)] - 38 = 0.69$$

$$F(64.3) = 1/750\ [64.3(56 - 38)/(64.3 - 62.4)] - 56 = 0.74$$

$$F(66.2) = 1/750\ [66.2(79 - 56)/(66.2 - 64.3)] - 79 = 0.96$$

The $\lambda^+(v_o)$ and $\lambda^-(v_o)$ values in Equations 1, 2, and 5 come from counting the number of vehicles that overtake and are overtaken by the observer car.

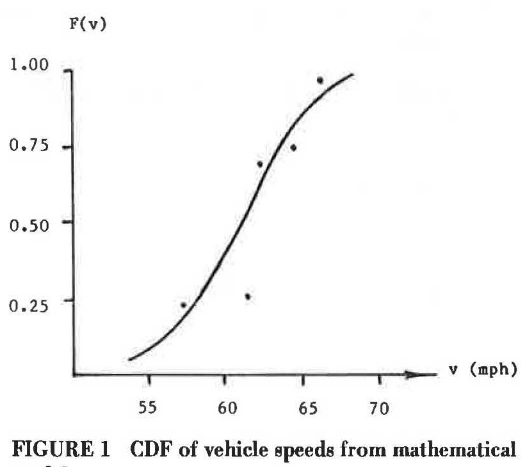

FIGURE 1 CDF of vehicle speeds from mathematical model.

Real traffic flow is not as well-behaved as the simplifying assumptions would indicate. Equations 4 and 5 are intended for use with small differences between $v^1{}_o$ and $v^2{}_o$ and with $\lambda^+(v_o)$ values that increase monotonically with v_o. Neither requirement is likely to be met in practice, however. It would not be practical to collect $\lambda^+(v_o)$ and $\lambda^-(v_o)$ counts for 1 mph increments of v_o. Secondly, there is no guarantee that $\lambda^+(v^2{}_o)$ will be greater than $\lambda^+(v^1{}_o)$, just because $v^2{}_o$ is greater than $v^1{}_o$. Finally, Equation 5 is sensitive to slight variations in $\lambda^+(v_o)$. When $v_o = 62.4$ mph, $\lambda^+(62.4) = 38$, which gives $F(62.4) = 0.69$. For $\lambda^+(62.4) = 37$, $F(62.4)$ becomes 0.61; for $\lambda^+(62.4) = 39$, $F(62.4)$ rises to 0.78. These factors explain why the real-life observations that formed the basis for Figure 1 put a point at $v_o = 62.4$ mph, $F(v_o) = 0.263$, well away from an otherwise fairly consistent set of points.

The curve in Figure 1 is, of course, a cumulative distribution function (CDF). From this CDF, the proportion of vehicles that are overtaken by the observer car can be estimated for any speed v_o. Furthermore, having a CDF makes it possible to convert it into the corresponding probability density function (PDF) that defines the speed distribution sought by the authors.

Reflections on the Mathematical Model

Clearly, the four simplifying assumptions are not strictly correct. The extent of their departure from reality has implications for our study as follows:

1. Drivers maintain constant speeds. Each driver has a speed he or she finds comfortable and would prefer to maintain (4). This speed is a function of that individual's driving attitude, ability, and experience. It is also influenced by the characteristics of the vehicle being driven: type (car, truck, etc.), size, handling, performance at certain speeds, and so forth. These factors support the first assumption, if driving conditions remain constant. But they do not. Furthermore, a driver cannot always drive at his or her "preferred" speed. Physical terrain (hills and curves) may be a limiting factor. So might vehicle densities, if they become great enough. Even at low densities, two or three cars properly positioned may be enough to impede or "push" a driver. Thus, even cruise control does not guarantee keeping to a preferred speed. Besides being boxed in, some drivers tend to adopt the speed of the vehicle just ahead, substituting the preference of the lead driver for their own. The adopted speed may be faster or slower than their own preference, but presumably the difference is not great. And, of course, the ultimate tempering influence on preferred speeds is the speed limit. An associated influence is the driver's perception of the enforcement level. What is the probability that one's speed will be detected? How much above the posted speed limit may one drive without being cited by the authorities? A final complicating influence may be the miscalibration of a vehicle's speedometer. Many speedometers read 2-8 percent high, that is, the speed shown may be 1.02-1.08 times the actual speed. For example, a car equipped with a speedometer that reads 65 mph, but reads 5 percent high, is actually traveling 65/1.05 = 61.9 mph. This 3 mph difference is often not explicitly known by the driver, who instead either (a) guesses at this value or (b) simply assumes a comfortable position in the traffic stream, which includes all the tempering factors mentioned.

2. No interaction between vehicles. Of course, vehicles in close proximity often do influence each other. One can be boxed in, be pushed to higher

speeds by a tailgating car or truck, or follow a lead car in a "platoon" of vehicles. Should this bother us in our study? Not really. If our central question is "How fast are vehicles moving?" it does not matter why they have a certain speed. Neither does it matter to the states' speed monitoring programs and the federal government, unless the speeds are so high that "corrective action" must be taken.

3. and 4. Traffic has reached steady state, in which entering vehicles follow a homogeneous Poisson process. The first half of this statement says that there is no abrupt change in the flow, such as there would be when a road reopens following a blockage. The second half says that Poisson distribution is appropriate for describing discrete random events. When traffic is light and when there is no obvious disturbing factor such as a traffic signal, the behavior of traffic may appear to be random, and the Poisson distribution will give satisfactory results (5). Neither of these assumptions is seriously incorrect. Traffic varies over the course of a day, but the transitions between high and low arrival rates are gradual enough to accept these assumptions for periods of analysis that are not long enough to include a significant change in arrival rates.

While none of the four assumptions are absolutely correct representations of reality, the real question is how well do they approximate the traffic stream being modeled. This can only be answered by gathering data on the phenomenon being described, which is what we describe next.

DATA COLLECTION

A more direct approach to characterizing the speed distribution is to drive at a variety of constant speeds for known distances, and record the number of vehicles that you pass (p') and that pass you (p). This was done with a cruise-control-equipped car on 817.9 mi of Interstate highways in the Midwest. Except where construction zones or impeding traffic prevented it, the car was operated at a constant speed between 52.8 and 69.1 mph for 5-mi segments. (Actually, the speedometer was read to the nearest integer mph, but timing the vehicle between mileposts determined that the observer car's actual speed was 0.960 times the speedometer reading. This is the reason for the unusual speeds used in the Equation 5 example calculations earlier and throughout this paper.) An overtaken vehicle was not added to the p' count if it was in the process of entering or exiting the main travel lanes of the Interstate, either using the on/off ramps or the shoulder. As soon as the observer car was able to resume the desired speed after a construction zone, speed trap, or rest break, data collection resumed. The validity of these data is analyzed later in this section.

Vehicle densities were estimated by counting the number of vehicles between the observer car and a distinctive landmark ahead, then measuring the distance to that point. Typical observed densities ranged from 10 to 40 vehicles per mile for two-lane (in each direction) Interstate highways.

There are several reasons why the observations could not be taken from a strictly homogeneous population of vehicle speeds.

1. Variations in terrain and roadway geometry.
2. Variations in percentage of heavy vehicles in the traffic stream.
3. Variations in vehicle density.
4. The "environment" of the highway: urban versus rural.
5. Enforcement of speed limits: visibility or reputation of the law enforcement agency.

The number of observations (p + p') made in a segment is a function of the observer car's speed, the segment length, and the density of traffic. As we shall show, if the distribution of vehicle speeds on a highway section is approximately normal with mean μ, p + p' should decrease as $|v_o - \mu|$ gets smaller. It is obvious that p + p' will increase if segment length increases, density increases, or both. The influence of densities and segment length on the p and p' counts can be eliminated by converting them to ratios as follows

$$\rho = p/(p + p');\ \rho' = p'/(p + p');\ \rho + \rho' = 1.00$$

These ratios are summarized in Table 1, with rural Interstate segments shown in a separate column. As expected, ρ' tends to be smaller at most observer car speeds in rural areas than in the overall dataset. The other sources of heterogeneity are not so easily eliminated, and we may not want to. We could decide to take p, p' counts only when certain conditions (e.g., level terrain, low densities) were met, or we could identify and separate our segments into hilly, level, urban, and rural groups. The roads traveled by the observer car were predominantly rural with gentle hills, but even the urban and hillier sections were not drastically different. (Observations were halted during a heavy thunderstorm, however.) In this paper, an attempt is made to estimate the speed distribution on all Interstate sections for which reliable data exist.

TABLE 1 Speed Data from Observer Car

Speed (mph) v_o	Rural ρ'	Total[a] ρ'
54.7	0.00	0.05
56.6	0.02	0.02
57.6	0.20	0.20
58.6	0.50	0.50
59.5	0.27	0.42
60.5	0.20	0.20
61.4	0.45	0.53
62.4	0.69	0.69
63.4	0.71	0.75
64.3	0.72	0.72
65.3	0.82	0.83
66.2	0.95	0.95
68.2	0.92	0.92
69.1	1.00	1.00

[a] Includes rural, urban, and suburban segments.

What are "reliable data"? For instance, it is correct for our purposes to take p, p' counts soon after a construction zone? Table 2 shows the summary of p, p' counts for the 16 segments that followed a construction zone. One would expect a noticeable increase in p + p' in these segments. Vehicles that eventually would have been seen from the observer car would pass or be passed by the observer car sooner, since construction zones tend to cause the formation of platoons. One would not necessarily expect a bias in the r' value, which is the p'/(p + p') value for these particular segments. Faster cars behind the observer car in the construction zone platoon may find some slower vehicles blocking them in the next open segment, but this is typically a 2-lane segment with at least twice the capacity of a 1-lane construction zone. The open segment was also 5 mi long in 14 of the 16 cases. The results of a chi-square test applied to the r' and ρ' columns in Table 2 support the hypothesis that the r' after

TABLE 2 Data Collection After Construction Zones

v_o	p	p′	r′	ρ′ (all)	r′ − ρ′
56.6	2	0	0.00	0.02	−0.02
57.6	15	2	0.12	0.20	−0.08
59.5	3	2	0.40	0.42	−0.02
61.4	6	18	0.75	0.53	+0.22
62.4	1	9	0.90	0.69	+0.21
64.3	3	3	0.50	0.72	−0.22
65.3	2	16	0.89	0.83	+0.06
66.2	0	13	1.00	0.95	+0.05
Total	32	63			

Note: r′ = p′/p + p′. Observation rate = 95 vehicles/76.9 mi = 1.235 vehicles per mile (not a standard density).

construction zones is not biased at the 95 percent confidence level. Furthermore, the expectation that more vehicles will be observed in these segments is also realized: 1.235 per mile versus 0.948 overall.

Should observations made in the presence or aftermath of highway police surveillance be included in our data base? Table 3 is similar in structure to Table 2, but involves only 5 segments over 13.75 mi. A significantly lower r' than ρ' would be expected in this case, but the data are too meager and contradictory to draw such a conclusion. These data were not discarded.

TABLE 3 Data Collection After Police Sighted

v_o	p	p′	r′	ρ′ (all)
59.5	5	0	0.00	0.42
62.4	1	7	0.88	0.69
63.4	2	0	0.00	0.75
64.3	0	4	1.00	0.72

Plotting the (v_o, ρ') values from Table 1 results in the points shown in Figure 2. Fitting a smooth curve through these points produces an "empirical" CDF much like that of Figure 1. This CDF can be used to test the fit of any distribution that is proposed as a model of the actual speed distribution along the highway.

The Two Approaches

In both the mathematical model and the empirical method described previously, the counts of vehicles

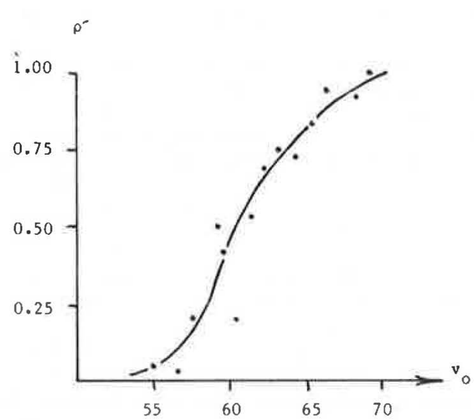

FIGURE 2 CDF of vehicle speeds from observer car data.

(p, p') over a range of speeds have been converted into proportions or ratios, which, in turn, have been plotted in CDF--$\Pr(V \leq v_o)$--form. The resulting S-shaped curves (Figures 1 and 2) are "similar," based on goodness-of-fit tests at the 95 percent confidence level. Thus, our data collection effort seems to validate the mathematical model's ability to describe the distribution of speeds, despite our critique of its simplifying assumptions, and subject to the limitations on the differences in v_o already discussed. The model's $F(v_o)$ values closely match the $\rho'(v_o)$ values generated for Table 1, except at v_o = 61.4 mph. What remains is to devise a procedure to convert either of the CDFs to the PDF of vehicle speeds and then test the results for accuracy.

TESTING THE METHOD

How do we test the model's ability to estimate the actual distribution of speeds in the highway section of interest? Ideally, radar could be used to record the exact speed of a vehicle at the time of observation, but this involves more expense or effort than is desired. Besides, there are complicating factors to consider. If a radar-derived speed is assigned to each vehicle, that speed ignores the variation of speeds a vehicle assumes as it reacts to different roadway geometry, traffic conditions, and driver behavior. A stationary radar site removes the variable of geometry, but at the moving observation post, vehicles are being viewed under a full range of conditions, which gives (theoretically) a better sample of overall vehicle speeds in the total traffic stream. However, the authors propose to limit the data collection to the simple question "When a vehicle is observed, is it passing or being passed?" Nothing can precisely be said about the other vehicle's speed, v, except $v > v_o$ or $v < v_o$. The difference is speeds may be 1, 5, or 20 mph. The observer can only guess, but need not (if the authors' method succeeds) even try.

Can a speed distribution be effectively reconstructed from this limited information? Equally important, against what can the estimates be compared? Speed monitoring data are usually gathered at a few fixed locations. Although care is taken to disguise the sites and to establish them in places unaffected by merging maneuvers and other factors, they are constrained to level highway sections where access to the recorders is easy and where protection of the equipment (e.g., by guardrails) is possible. Each location used probably has some bias as a result of prevailing vehicle mix, variations in vehicle densities, weather conditions, and other factors. If one is interested in what speeds exist in the entire traffic stream during a particular trip, only a considerable number of perfectly disguised recording stations along the route could give the desired distribution. For reasons of economy and reproducibility of results, a simulation model was developed.

The Simulation Model

The authors wished to sample speeds of vehicles in the traffic stream by observing whether the driver is passing them ($v_o > v$) or they are passing the driver ($v > v_o$). Then this sample and a constructed PDF of speeds are compared with the "actual" speed distribution for the traffic stream in which the authors were traveling. For reasons already mentioned, the actual distribution is not possible to accurately describe. But, for these testing purposes, it is not really necessary to know the exact distribution of an actual traffic stream. If one could create an exact distribution, pretend not be know its shape, then sample from it to generate an estimated distribution, one would have the basis for testing the authors' method. A simulation model can create such distributions.

Steps in Simulation Program

1. Reading input values that include the following;

a. Parameters of distribution describing vehicle speeds;

b. Traffic density (vehicles per mile);

c. Speed of observer car (v_o);

d. Termination criteria as follows;

• Length of observation section, Δx (mi),

• Length of time that v_o will be maintained (min), and

• Minimum number of observations k* to be made at v_o mph;

e. Speed for random number generator.

2. Increment count of vehicles observed, k = k + 1.

3. Generate the location x_k of the k^{th} vehicle with respect to the observer car ($x_o = 0$) at the start of the observation period, sampling from a uniform distribution.

4. Generate the k^{th} vehicle's speed, v_k, using the hypothesized distribution.

5. If $x_k > x_o$, go to step 6. If $x_k \leq x_o$, calculate whether the k^{th} vehicle will overtake the observer car before the observation period terminates. If so, p = p + 1. Go to step 7.

6. Calculate whether the observer car will overtake the k^{th} vehicle before the observation period terminates. If so, p' = p' + 1.

7. If the observation period has not ended, return to Step 2.

8. Stop simulation. Print summary of observations made.

The most interesting product of the simulation program is the plot (Figure 3) of the distribution of speeds for the vehicles that were seen from the observer car. These speeds are not known to the observer, except to the extent that they make up the p and p' counts, but their distribution is at once fascinating and important to the estimation method. Figure 3 illustrates how the actual distribution of vehicle speeds (dashed curve) is distorted when viewed from a moving vehicle. The reason for the dip in curve (b) near v_o is easy to understand.

• For a vehicle with speed v_k not much different from v_o, its initial location must be relatively close to x_o to expect meeting the observer car during the study period.

• For a given v_o, the probability of the k^{th} vehicle meeting the observer car during the study period increases as $|v_k - v_o|$ increases, especially as v_k moves in the direction of the mode of the speed distribution.

• However, as v_k begins to take on extreme values (in the tails of the speed distribution) that are less likely to occur, this decreases the probability of a vehicle with such speed even existing to meet the observer car.

Note that both curves in Figure 3 are drawn as PDFs. Each encloses an area of 1.00, based on their respective definitions of an event. However, the speed distribution of the population (the dashed curve) represents a greater number of vehicles in the study section, since a majority of these vehicles will never meet (be sampled or observed from) the observer car. The standard deviation for curve (b) is greater than that for (a) because there are fewer speeds observed near the mean for curve (b).

HOW TO USE THE METHOD

The task before us is to take a few p, and p' counts and convert them into an estimate of the speed distribution's parameters. The authors are only concerned with putting each observed vehicle into one of two categories: $v < v_o$ or $v > v_o$.

At each v_o, the data collected will be used to locate a point on a CDF such as in Figure 2. The accuracy of that point's location $p'(v_o)$ with respect to its correct location should improve with an increase in the length of time at v_o, since $\rho'(v_o)$ will be based on a larger sample size, p + p'. However, each time the v_o is changed, a new "view" of the distribution is obtained, which the authors are trying to reproduce. Because each view is so limited (either $v_o > v_k$ or $v_k > v_o$), the greater the number of v_o's that are adopted, the better the CDF's shape

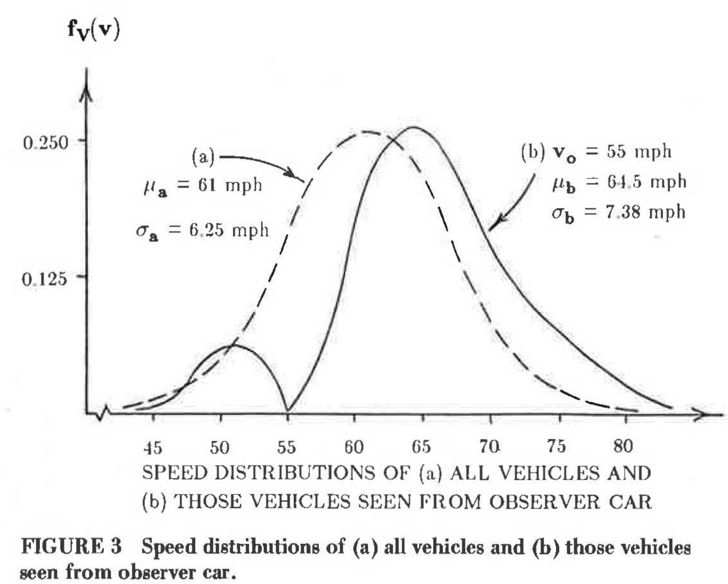

FIGURE 3 Speed distributions of (a) all vehicles and (b) those vehicles seen from observer car.

is likely to be approximated. For a trip of moderate length, say 100 mi, a trade-off occurs. One can travel at two different speeds for 50 mi each, or at 10 different speeds for 10 mi each, or any other combination of distance (Δx) and number of different speeds (n) whose product does not exceed 100 mi. The first strategy would seem to provide two points of high quality, while the second approach gives ten fewer reliable points through which to fit a CDF.

Converting a CDF to a PDF

Say, for example, that one chose to travel at a v_o of 55 mph for 50 mi, and that the simulation program reported that $\rho'(55) = .104$. This means that $Pr(v_k < 55 \text{ mph}) = .104$. Because the CDFs from both the mathematical model and the empirical method (Figures 1 and 2) resemble a CDF derived from a normal distribution, one is justified in assuming a normal distribution. Branston (6) supports this choice of distribution. Thus, we seek the standard normal deviate

$$z = (v_o - \mu)/\sigma$$

that causes $\Phi(z) = .104$. This is represented by $\Phi^{-1}(.104)$, the solution to which can be found in a CDF table of the standard normal distribution. Here,

$$\Phi^{-1}(.104) = -1.26 = (v_o - \mu)/\sigma = (55 - \mu)/\sigma \quad (6)$$

with μ and σ being the two parameter values to be solved for. Equation 6 can be rearranged to be

$$\hat{\mu} - 1.26\,\hat{\sigma} = 55 \quad (6')$$

Driving at a different v_o, say, 65 mph, gives $\rho'(65) = 0.787$. This becomes $\Phi^{-1}(.787) = 0.795$ and, in a few steps,

$$\hat{\mu} - 0.795\,\hat{\sigma} = 65 \quad (7)$$

Solving Equations 6' and 7 simultaneously gives $\hat{\mu}$ = 61.1 mph and $\hat{\sigma}$ = 4.87 mph. Trying other v_o values gives an expanded number of pairs of values with which to find $\hat{\mu}$ and $\hat{\sigma}$. Table 4 shows how these estimates will vary with choices of v_o pairs. Insuring that the number (n) of observer speeds (v_o) exceeds two produces $n!/2!(n-2)!$ solutions for $\hat{\mu}$, $\hat{\sigma}$ to be examined for trends and clues, such as those solutions that should be discarded.

TABLE 4 Solutions for $\hat{\mu}$, $\hat{\sigma}$

v_o pairs	$\hat{\mu}$	$\hat{\sigma}$
55 and 60	60.89	4.67
60 and 65	61.0	5.08
65 and 70	61.6	4.16
55 and 65	61.1	4.87
60 and 70	60.85	4.55
55 and 70	60.77	4.59
Avg. values	61.04	4.65

Note: Δx_o = 50 mi, μ = 61 mph, and σ = 6.25 mph.

At this point, the authors could select the "most central" of the six solutions in Table 4, say, $\hat{\mu}$ = 60.89 with $\hat{\sigma}$ = 4.67, adopt the average of the parameter solution values ($\hat{\mu}$ = 61.04, $\hat{\sigma}$ = 4.65), or use any legitimate variation. In this example, the estimate of $\hat{\mu}$ would be quite accurate, but $\hat{\sigma}$ is consistently about 25 percent below the 6.25 value entered into the simulation program. Table 5 and Figure 4 illustrate why this is so.

The solid curve labeled "$\Phi(z)$" in Figure is the CDF for the normal distribution the authors are attempting to duplicate from the observed data. The curve with short dashes--"$\rho'(v_o)$"--is the CDF constructed from the proposed method, with (Δx = 1,000 mi) to ensure statistical stability. Note how it starts below the $\Phi(z)$ curve, crosses it at approximately 0.50, and finishes above it. The $\rho'(v_o)$ curve is "steeper" than the $\Phi(z)$ curve; therefore, it will have a narrower PDF than $\Phi(z)$'s target PDF.

TABLE 5 Comparison of CDF Values

v_o:	55	60	65	70
$\Phi(z)$	0.1685	0.4364	0.7389	0.9251
$\rho'(v_o)$	0.080	0.382	0.821	0.976
$F(v_o)$	0.044	0.244	0.554	0.816
$R(v_o)$	0.244	0.554	0.816	1.00

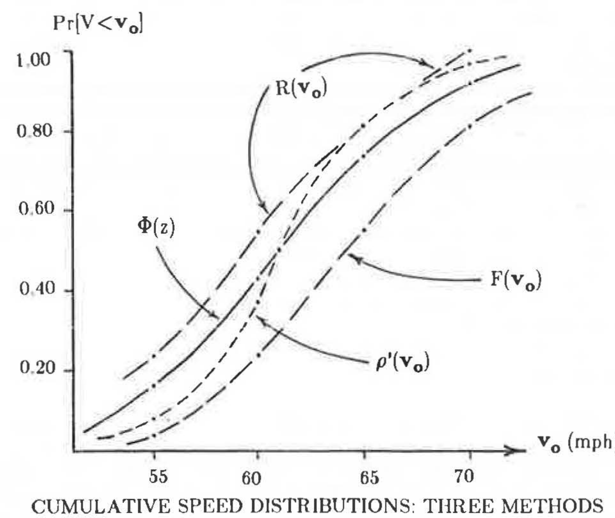

FIGURE 4 Cumulative speed distributions: three methods.

The "$F(v_o)$" curve is based on the use in Equation 5 of the same data Δx = 1,000 mi) that went into the $\rho'(v_o)$ curve. Note how $F(v_o)$ is consistently lower than the desired $\Phi(z)$ value. However, the $F(v_o)$ curve has one very desirable characteristic: its slope is much like that of the $\Phi(z)$ curve. On the theory that the $F(v_o)$ curve is too low because Equation 5 does not handle large changes in v_o well, the authors rearranged that equation to get

$$R(v^1_o) = 1/q\ \{v^1_o[\lambda^+(v^1_o) - \lambda^+(v^2_o)] \div (v^1_o - v^2_o) - \lambda^+(v^1_o)\} \quad (5')$$

Because this is just Equation 5 with v^1_o and v^2_o reversed (and with v^2_o still greater than v^1_o), this is called the Reverse $F(v_o)$ Curve, denoted by $R(v_o)$. The $R(v_o)$ curve is consistently above $\Phi(z)$, but with a similar slope. The "average" of the $F(v_o)$ and $R(v_o)$ curves would approximate the $\Phi(z)$ curve quite closely. In addition, the common structure of Equations 5 and 5' gives rise to a repetition of solution values (see .244, .554, and .816 in Table 5). This allows for a check on the accuracy of calculations or the elimination of the three redundant ones.

By using .5 $[F(v_O) + R(v_O)]$ as input to Equation 6, the same procedure that built Table 4 provides the entries for Table 6. A highway section of 1,000 mi is too long to be realistic, but it is used here to guard against statistical aberrations in the p and p' counts that can occur with small samples (short sections). The μ estimates are slightly high [since $F(v_O)$ and $R(v_O)$ are not quite symmetric about the $\Phi(z)$ curve], but $\hat{\sigma}$ is close to the desired 6.25 value of σ, thanks to the similarity in the slopes of the three CDFs involved.

TABLE 6 Solutions for $\hat{\mu}$, $\hat{\sigma}$ Using $F(v_O)$ and $R(v_O)$ Values

v_O Pairs	$\hat{\mu}$	$\hat{\sigma}$
55 and 60	61.58	6.21
60 and 65	61.73	6.80
65 and 70	62.18	5.88
55 and 65	61.88	6.49
60 and 70	61.60	6.31
55 and 70	61.65	6.27
Avg. values	61.77	6.33

Note: Δx_O = 1,000 mi, μ = 61 mph, and σ = 6.25 mph.

SUMMARY

The method developed in this paper offers some advances in the practical aspects of estimating the highway speed distribution from a moving vehicle. Mathematical models of the sort described by Equation 4 call for a fully specified CDF in order to produce the PDF. This specification is seldom possible. What is possible is a count of vehicles overtaken by (and overtaking) an observer car. Our first proposed method estimated μ well, but consistently underestimated σ. The mathematical model's CDF was consistently low, but had the correct slope. Use of this CDF and its "reverse" counterpart in a step preliminary to our method of solving simultaneous equations yielded good estimates of μ and σ.

The result is a description of highway speeds which, in some ways, is superior to the stationary speed monitoring summaries in that a more complete picture is obtained of the traffic stream under a variety of driving conditions.

ACKNOWLEDGMENTS

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Causal Analysis of Accident Involvements for the Nation's Large Trucks and Combination Vehicles

T. CHIRA-CHAVALA and DONALD E. CLEVELAND

ABSTRACT

The chance of accident involvements of the Interstate Commerce Commission-authorized, large, single-unit trucks and tractor-trailers was investigated using the 1977 Bureau of Motor Carrier Safety accident and the Highway Cost Allocation Study exposure data. The model used was discrete-multivariate and capable of simultaneously analyzing both the accidents and the exposure. The variables that were found to be important predictors of accident involvements include trailer style, vehicle configuration, number of axles of power unit, trip length, road class, road surface condition, loading status, day/night, driver experience, and driver age. Particularly high accident involvement rates, of 200 involvements per 10^8 mi or higher, were shown by all van singles in local service, 3-axle-tractor singles in local service, 2-axle straight trucks in local service, and flatbed doubles in over-the-road service. Low accident involvement rates of less than 50 involvements per 10^8 were shown by all 3-axle straight trucks and 2-axle straight trucks in over-the-road service. Van singles and tanker singles in over-the-road service showed moderate involvement rates (less than 100 involvements per 10^8 mi), while 2-axle-tractor van doubles and 2-axle-tractor tanker doubles showed higher rates (120 to 200 involvements per 10^8 mi).

This paper contains the results of an investigation of the association between the chance of accident involvements and several influencing factors for the nation's large single-unit trucks and tractor-trailers. The methodology developed for this study is aimed at obtaining stable estimates of the probabilities of accident involvements. The findings are useful as input for policy planning (including usage regulations for certain types of trucks and their route assignments, driver education, and training programs). They also provide input for vehicle tests and simulations, accident countermeasures, as well as identifying gaps in data collection efforts concerned with truck accidents and usage.

STATEMENT OF THE PROBLEM AND LITERATURE REVIEW

The current Federal Surface Transportation Act, passed by Congress in December of 1982, lifted the restriction that long barred the operation of large tractor-trailers in many states. However, the highway safety of these trucks is not fully understood. There is also no consensus on the estimates of the various accident characteristics of these trucks.

As with most other traffic accident problems, direct theoretical work has not led to sufficient understanding of how accidents involving these trucks occur. Data collected from actual past accident experience and truck usage, when properly analyzed, can provide insight into this complex phenomenon.

Several past major accident analyses of these trucks (1-3) have produced vastly different findings on their safety records. Vallette, McGee, Sanders, and Einger (1) reported that "doubles" (tractors pulling two trailers) had much higher accident involvement rates than both single-unit trucks and "singles" (tractors pulling one trailer). Their study was based on data collected from selected locations in California and Nevada. T-tests and analysis of variance were used to analyze the data.

Glennon (2) conducted a study of accident involvements of singles and doubles for a commercial carrier's fleet and reported that there was no statistically significant difference in the accident rates between singles and doubles. His study was a matched-pair analysis controlling for factors such as origin-destination pairs, routes, and trip length.

The Bureau of Motor Carrier Safety (BMCS) reported the accident rates for singles and doubles for each year from 1969 to 1976 (3). The overall number of accidents per million truck miles for doubles was found to be consistently lower than for singles, with the exception of 1975 when doubles showed a slightly higher rate.

The sources of incompatibility in the findings of past accident-analysis studies included (a) most studies only examined a special population of trucks (i.e., from certain companies, states, or regions of the country). Often, the selection of the samples was not necessarily random; thus, it is difficult to use or extrapolate their findings at the national level; and (b) methods of analyzing accident rates, t-tests, and/or analysis of variance in which one or two variables were investigated at a time, have shortcomings. One of these is the implicit assumption that these tests were carried out for "homogeneous" populations. That is, there were no other significant "confounding" factors at play. Such an assumption, when not met, gives rise to "Simpson's Paradox" (4) and, therefore, model misspecification and possible incorrect findings.

This study is based on the two currently available national data sets: the BMCS file for the accident involvements, and the Highway Cost Allocation Study (HCAS) file for truck mileage and uses. The model estimation technique for accident involvements is discrete-multivariate and capable of simultaneously adjusting for the difference in truck usage and mileage (the exposure). It also allows a large number of independent variables to be simultaneously examined.

THE DATA

BMCS

The BMCS file contains information on accidents involving interstate motor carriers that are subject to the Department of Transportation Act of 1966 (49 United States Code 1655). These carriers are required to report to the BMCS any accidents involving their vehicles that result in death, injury, or property damage over $2,000. Excluded are occurrences that involve any boarding and alighting from a stationary vehicle, loading and unloading of cargo, and farm-to-market agricultural transportation. The accident information is reported to the BMCS by the carriers themselves on standard forms.

There are altogether 74 variables and over 30,000 accidents reported each year. The variables provide information on the place and time of accidents, events leading to accidents, accident consequences, driver and occupation, vehicle description, road conditions, and some environmental conditions.

HCAS

The HCAS file is a modification of the Truck Inventory and Use Survey (TIU) (5). It provides information on vehicle factors and some operational characteristics of the nation's truck population, other than those owned by federal, state, and local government agencies. There are altogether 96 variables recorded. The original TIU file is based on a stratified random sample of trucks in the country. Truck operators were asked to furnish information on their vehicles on a standard questionnaire.

METHODOLOGY

Large single-unit trucks (straight trucks) are defined in this paper as those over 10,000 lb. Tractor-trailers (combination vehicles), whether singles or doubles, can operate with a variety of trailers, the most common of which are vans, flatbeds, and tankers. In this study, the population of large single-unit trucks and combination vehicles are limited to the ICC-authorized carriers, which were not carrying farm products. The scope of the analysis is for a 12-month period in 1977.

The lack of information on road class, environment, and drivers in the HCAS file has led to dividing the model estimation into two parts: "casual" and "deductive" models. In a causal model, the association between the probabilities of accident involvements and the independent variables, which are available in both files, is quantified. Deductive modeling assesses the influence of those independent variables that are missing from the exposure data file: road class, day-night, road surface condition, region of the country, loading status, driver age, driver experience, and so forth.

Causal Model

An accident-involvement model expresses the chance of involvements in terms of the effects of the significant independent variables, adjusted for the truck miles of travel (or exposure). The formulation of the accident-involvement model follows in Figure 1 for a simple case of two independent variables. For a larger number of the independent variables, the same derivation applies.

Boxes (i) and (ii) represent the contingency tables for the accident involvements and the truck

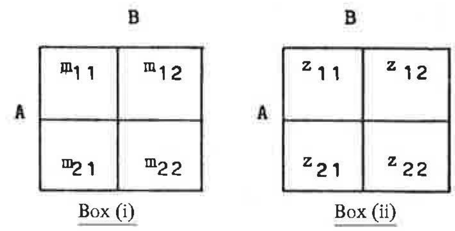

FIGURE 1 Formulation of the accident-involvement model for two independent variables.

mileage, and A and B represent the two independent variables whose effects on the accident involvements are under investigation. They have I and J levels, respectively, the variable m_{ij} is the number of accident involvements indexed by the levels of A and of B, and Z_{ij} is the exposure, also indexed by the levels of A and B. The model for accident-involvement can be expressed as:

$$P\{\text{an involvement adjusted for mileage}\} = f\{A,B\} \quad (1)$$

or

$$\text{Log } \{m_{ij}/z_{ij}\} = w + w_i^A + w_j^B + w_{ij}^{AB} \quad (2)$$

$$\text{Such that } \sum_i w_i^A = \sum_j w_j^B = \sum_i w_{ij}^{AB} = \sum_j w_{ij}^{AB} = 0$$

where

w = the grand mean,

w_i^A = the main effect of A,

w_j^B = the main effect of B, and

w_j^{AB} = the interaction between A and B.

Because the left-hand side of Equation 2 is expressed as the number of accident involvements per truck mile (or an accident involvement rate), this model is referred to as an accident-rate model. Whereas accident involvements (m_{ij}) are multinomial frequency data, truck miles of travel (Z_{ij}) are not. This has led to the following model-estimation technique.

Estimation of the model as represented by Equation 2 involves first fitting a log-linear model (6) to the accident data of box (i) and then adjusting this fitted model by the exposure of box (ii). This adjustment is necessary because of the differences in truck usage and mileage. The estimation procedure involves the following steps:

1. A log-linear model is fitted to the accident data of box (i). This model configuration can be expressed as:

$$\text{Log } \{m_{ij}\} = u + u_i^A + u_j^B + u_{ij}^{AB} \quad (3)$$

2. The model configuration so obtained is then applied to the exposure data of box (ii). This serves two purposes: (a) to determine the magnitude of the corresponding model terms for the exposure, and (b) to obtain the "smoothed" estimates of cell exposure. This is desirable because the observed cell exposure in a large contingency table can vary from a small to a large value, including zero. Usually, such zero cells are small cells and not structured zeros (i.e.,

cannot happen). They are zero because of the sample design. The result of this step can be expressed as:

$$\text{Log}\ \{z_{ij}\} = v + v_i^A + v_j^B + v_{ij}^{AB} \quad (4)$$

3. The estimated accident-involvement model as represented by Equation 3 is adjusted by the exposure. The resultant accident-involvement rate model can be expressed as:

$$\text{Log}\ \{m_{ij}/z_{ij}\} = w + w_i^A + w_j^B + a_{ij}^{AB} \quad (5)$$

where

$w = u - v$,
$w_i^A = u_i^A - v_i^A$,
$w_j^B = u_j^B - v_j^B$, and
$w_{ij}^{AB} = u_{ij}^{AB} - v_{ij}^{AB}$.

The goodness-of-fit measure for the accident involvements (Equation 3) is asymptotically distributed as chi-square with appropriate degrees of freedom as follows:

$$G^2 = -2\ \Sigma\ (\text{observed})\ \text{Log expected/observed} \quad (6)$$

Because of the sampling factors of the surveyed mileage and the fact that the mileage data do not have a multinomial distribution, the G^2 for the exposure is not a meaningful goodness-of-fit measure. In fact, the sampling factors will inflate the G^2 value for the exposure (7). The role of the exposure in the model estimation is then limited to adjusting the accident involvements of the trucks. The exposure does not affect the goodness-of-fit or the selection of the "best" accident-rate model.

In the event there are a number of model configurations that fit the accident involvements reasonably well, the following criteria are used to select the best accident-rate model:

1. Fewer high-order terms or higher degrees of freedom;
2. Estimated accident rates are close to observe rates; and
3. A reasonable goodness-of-fit for the accident involvements.

Deductive Modeling

This involves estimating a contingency table for the exposure to include the variable(s) whose effect on the chance of accident involvements (in the presence of all the significant independent variables from the causal modeling) is being investigated. The assumption for estimating this contingency table is that the variable(s) in question is (are) not significant. The estimated exposure so obtained is then assessed to see if it is realistically reasonable. If it is not, the variable(s) in question can be said to be significant. Furthermore, by examining this estimated exposure on a cell-by-cell basis, the manner in which this particular variable(s) affects (affect) the accident-involvement rates can be identified in greater detail. Deductive analysis can be used to examine one variable or a group of variables whose interactions with one another may be known a priori or suspected.

The deductive analysis involves the following steps:

1. A contingency table of accident involvements is obtained from the BMCS file. The table is cross-classified by all the significant variables from the casual modeling plus the variable(s) that is (are) being investigated.
2. A similar contingency table for exposure is obtained by estimating the exposure for all cells so that the variable(s) under investigation will be nonsignificant. (This table is cross-classified by the same variables as in step 1.)
3. The accident data and the estimated exposure obtained in step 2 are used to estimate the accident-rate model using the procedure described in the section entitled "Causal Model." If the variable(s) under investigation was (were) indeed nonsignificant, all the estimated model terms (w-terms of Equation 5) that involve that variable should be small or zero. If these model terms are not small, steps 2 and 3 are repeated until they are.
4. The reasonableness of the "best" estimated exposure table is assessed on a cell-by-cell basis and overall. If this estimated exposure is considered unrealistic, the variable(s) in question is (are) significant. Examining the estimated exposure on a cell-by-cell basis will help identify the pattern of the effect of such a variable or variables.

RESULTS OF MODEL ESTIMATION

Causal Model

The independent variables initially included in the causal analysis were those that were available in both the BMCS and the HCAS files. They are:

1. Vehicle configuration--single, double, or straight truck;
2. Trailer body style: van, flatbed, or tanker;
3. Number of axles of power unit: 2- or 3-axle;
4. Model year--pre-1974 (older) or post-1974 (newer);
5. Trip length--over-the-road or local service;
6. Number of axles of the trailer(s);
7. Vehicle length;
8. Gross vehicle weight (GVW);
9. Registered weight of vehicle;
10. Cargo type; and
11. Region of the country (or state) in which accident occurred.

The information on the first six variables is reasonably complete and the levels of these variables are compatible in both the BMCS and the HCAS files. However, the distributions of number of trailer axles for flatbeds and tankers resulted in a large number of empty cells for multi-dimensional contingency tables. This variable was therefore not included in causal modeling. Also excluded from causal modeling was vehicle length because it was recorded differently in the two files; the BMCS file recorded total length while the HCAS file recorded the length of cargo compartments.

The GVW in the BMCS file reflects the actual gross weights of the trucks at times of accidents. This variable in the HCAS file indicates the maximum weights that the trucks had operated in the past twelve months of the survey period. Because of this discrepancy, GVW was excluded from causal modeling. The registered weight variable also had recording inconsistency: some registered vehicle weights from the HCAS file reflect empty weights while some others reflect the allowable GVWs. It was therefore excluded from causal modeling. The weight variable, however, remained a candidate for deductive modeling.

Cargo type is another variable in which considerable recording incompatibility, caused by vastly different definitions of cargo types, exists in the two files. Considerable effort was made here to correct these mismatched cargo types in the two files. Unfortunately, the results were not satisfactory. It was noted that cargo type was highly correlated with vehicle configuration and trailer body style. Its exclusion from causal modeling was, therefore, not critical in the presence of the other two variables.

Regions of the country where the accidents occurred would be a good surrogate for factors that are usually not recorded or measured in both the accident and the exposure files. They are factors such as traffic density, traffic mix, operating speeds, general terrain, road or highway standard, traffic enforcement, and other ambient environmental characteristics that may affect the chance of accidents. Although the BMCS file contains both state of accident and state of registration data, the HCAS file only contains the latter. It is common for vehicles registered in, say, an eastern state to be operated in western states, and vice versa. Delaware, for example, accounted for a high percentage of total registrations in the country, yet it showed only a small proportion of in-state accidents. Because of the potentially important contribution of the regions of the country where accidents occurred toward explaining the chance of accident involvements, many attempts were made to create this variable for the HCAS file using the information on region of registration. The results of these attempts, however, were not satisfactory (8). It was thus excluded from causal modeling although it remained a candidate for deductive modeling.

At this stage of the analysis, there were five independent variables left for causal-model estimations: vehicle configuration, trailer style, number of axles of power unit, model year, and trip length. Because straight trucks do not usually have different trailer styles, a contingency table of accident involvements or exposure cross-classified by these five variables resulted in too many empty cells, many of which were "structured" zero. This suggested that separate modeling for the following two subsets were appropriate. They are: (a) combination vehicles and (b) straight trucks.

Combination-Vehicle Subset

The combination-vehicle subset was by far the larger of the two subsets. Table 1 gives the contingencies for the BMCS accident involvements for the ICC-authorized combination vehicles (excluding farm products). Table 2 gives contingencies for the HCAS annual truck miles of travel.

The "best" accident-rate model for the combination-vehicle subset, based on the estimation technique of the section entitled "Causal Model," was found to include the following terms:

[1345], [123], [124], [125], [234], [235], and [245] (7)

where

V1 = trailer style,
V2 = vehicle configuration,
V3 = number of axles of power unit,
V4 = model year,
V5 = trip length, and
[1345] = an interaction among V1, V3, V4, and V5, and so on.

TABLE 1 Accident Involvements of ICC-Authorized Carriers Excluding Those Carrying Farm Products

Trip Length	Model Year	No. of Axles (tractor)	Single/ Double	Van	Flatbed	Tanker
Over the road	Old	2	S	866	107	64
			D	270	–[a]	32
		3	S	3,135	2,027	861
			D	43	21	8
	New	2	S	607	53	35
			D	387	13	18
		3	S	5,022	1,334	931
			D	87	12	4
Local	Old	2	S	859	17	8
			D	18	–[a]	3
		3	S	523	66	97
			D	7	3	–[a]
	New	2	S	458	9	4
			D	13	–[a]	–[a]
		3	S	295	27	93
			D	–[a]	–[a]	–[a]

SOURCE: 1977 BMCS.

[a]Zero accident involvements and/or miles.

TABLE 2 Annual Mileage (in 10^6 Miles) of ICC-Authorized Carriers Excluding Farm Products

Trip Length	Model Year	No. of Axles (tractor)	Single/ Double	Van	Flatbed	Tanker
Over the road	Old	2	S	1,323.34	161.42	78.84
			D	230.96	–[a]	17.46
		3	S	2,967.58	1,183.42	874.25
			D	84.16	4.98	18.36
	New	2	S	826.06	122.71	97.34
			D	248.06	5.06	10.59
		3	S	5,188.33	1,196.81	897.33
			D	90.14	10.54	9.31
Local	Old	2	S	522.18	35.26	6.74
			D	27.33	–[a]	3.91
		3	S	258.19	77.15	69.97
			D	10.92	5.31	–[a]
	New	2	S	228.89	8.41	8.58
			D	7.04	–[a]	–[a]
		3	S	51.29	24.88	35.80
			D	–[a]	–[a]	–[a]

[a]Zero accident involvements and/or miles.

Because this model is a hierarchical model, it also contains, in addition to the preceding seven terms, all the lower interaction terms as well as the main effects of all five variables.

The G^2 value for the accident involvements was 17.40 for 9 degrees of freedom (p-value = .043), indicating a reasonable fit for the accident involvements. The estimated overall mean accident rate for all combination trucks, based on the model configuration of Equation 7, was 120.4 accident involvements per 10^8 vehicle mi.

Observed and Estimated Accident Rates

The observed and the estimated accident-involvement rates are given in Table 3. The rates indicate that the estimated accident-rate model fit the data quite well. There were seven cells in which the observed and the expected accident rates differed by more than 15 percent. These were mostly cells with a relatively small number of accident involvements.

TABLE 3 Observed and Estimated Involvement Rates, per 10^8 Miles, for Combination Vehicles

Configuration	Trip Length	No. of Axles (tractor)	Model Year	Observed Van	Observed Flat	Observed Tanker	Estimated Van	Estimated Flat	Estimated Tanker
Single	OR	2	New	73.48	43.19	35.96	72.64	46.10	37.81
			Old	65.44	66.29	81.18	65.96	63.95	78.72
		3	New	96.79	111.46	103.75	96.93	111.21	103.41
			Old	105.64	171.28	98.48	105.44	171.66	98.68
	Local	2	New	200.10	107.02	46.62	199.74	98.52[a]	42.02[b]
			Old	164.50	48.21	118.69	165.02	50.67	92.85
		3	New	575.16	108.52	259.78	580.55	108.33	257.67
			Old	202.56	85.55	138.63	201.49	84.83	143.36
Double	OR	2	New	156.01	256.92	169.97	159.20	242.02[a]	122.22
			Old	116.90	—[c]	183.28	114.24	—[c]	203.73
		3	New	96.52	113.85	42.96	89.52	132.99[a]	68.29[b]
			Old	51.09	421.69	43.57	57.95	342.52	39.29[a]
	Local	2	New	184.66	—[c]	—[c]	192.74[a]	—[c]	—[c]
			Old	65.86	—[c]	76.73	69.71	—[c]	116.36[b]
		3	New	—[c]	—[c]	—[c]	—[c]	—[c]	—[c]
			Old	64.10	56.50	—[c]	63.13[a]	69.51[b]	—[c]

Note: OR = over-the-road service.

[a] Fewer than 15 accident involvements.
[b] Fewer than 5 accident involvements.
[c] Zero accidents and/or miles.

The truck types that showed extremely high accident involvement rates were:

1. Newer, 3-axle-tractor van singles in local service (580 involvements per 10^8 mi);
2. Older, 3-axle-tractor flatbed doubles in over-the-road service (342 involvements per 10^8 mi); and
3. Newer, 3-axle-tractor tanker singles in local service (258 involvements per 10^8 mi).

Those with high accident involvement rates (approximately 160 to 200 involvements per 10^8 mi) were:

1. All van singles in local service;
2. Newer, 2-axle-tractor van doubles in local service;
3. Newer, 2-axle-tractor van doubles in over-the-road service;
4. Older, 2-axle-tractor doubles in over-the-road service; and
5. Older, 3-axle-tractor flatbed singles in over-the-road service.

Overall Influence of Independent Variables

Trailer Body Style

Among all the doubles in over-the-road service, flatbeds showed a much higher accident rate than did tankers or vans. Among 3-axle-tractor singles in over-the-road service, flatbeds showed a higher rate than did vans or tankers. For 2-axle-tractor singles, the rates were similar for vans, flatbeds, and tankers. For singles in local service, vans were found to have much higher accident rates than did tankers or flatbeds.

Vehicle Configuration

The influence of vehicle configuration (single or double) in over-the-road service is as follows:

1. Two-axle-tractor van doubles (the majority of van doubles) showed approximately a 30 percent higher accident rate than 3-axle-tractor van singles (the majority of van singles).
2. Two-axle-tractor tanker doubles (the majority of tanker doubles) showed a higher accident rate (1.2 to 2) than did 3-axle-tractor tanker singles (the majority of tanker singles).
3. Flatbed doubles showed a higher accident rate than did flatbed singles.

Number of Axles of Power Unit

The overall influence of this variable was different for the single and the double populations. For doubles in over-the-road service, 3-axle tractors always showed much lower rates (in general, approximately 50 percent lower) than did 2-axle tractors. For singles, 3-axle tractors showed higher rates than did 2-axle tractors under similar conditions.

Model Year

The overall influence of model year (pre-1974 or old, and post-1974, or new) was found to be smaller than the other four independent variables. For singles engaged in local service, newer models showed higher accident rates than did older models. For singles in over-the-road service, the influence of model year was usually small. For doubles, the pattern was less clear.

Trip Length

The overall influence of this variable was prominent for van and tanker singles. Local service showed considerably higher accident rates than did over-the-road service (up to 5 times for van singles and up to 2.5 times for tanker singles). Its influence on flatbed singles was less pronounced. The influence of trip length on doubles was difficult to assess due to lack of data for doubles engaged in local service.

Straight-Truck Subset

Table 4 gives contingencies for the BMCS-reported accident involvements for the ICC straight trucks.

TABLE 4 Accident Involvements and Exposure for Straight Trucks

Trip Length	Model Year	No. of Accidents Involved		No. of Miles (10^6)	
		2 Axle	3 Axle	2 Axle	3 Axle
Over the road	Old	99	40	189.35	249.17
	New	128	33	259.48	193.84
Local	Old	694	44	413.36	98.43
	New	373	27	181.60	90.69

Note: Data exclude farm products.

The table is a cross-classification of three variables. They are as follows:

1. V1--number of axles (2-axle or 3-axle),
2. V2--model year (pre-1974 or post-1974), and
3. V3--trip length (over-the-road or local service).

Table 4 also gives a similar contingency table for the exposure (miles of travel) that was obtained from the HCAS file.

The accident-rate model for straight trucks was estimated using the procedure described in the section entitled "Causal Model." The best-fitted model was found to contain the following model configuration:

[13] and [23] (8)

The G^2 value for the accident involvements was 3.04 for 2 degrees of freedom, indicating a reasonable fit for the accident involvements. The observed and the estimated involvement rates are given in Table 5. The table indicates that 2-axle straight trucks in local service had high accident rates (approximately 180 to 200 involvements per 10^8 mi). On the other hand, 3-axle straight trucks were found to have low accident rates, particularly those in over-the-road service (approximately 17 involvements per 10^8 mi). Two-axle straight trucks in over-the-road service and 3-axle straight trucks in local service also showed low to moderate rates (approximately 40-50 involvements per 10^8 mi). The estimate of the overall mean involvement rate for straight trucks was 48.6 involvements per 10^8 mi.

TABLE 5 Observed and Estimated Involvement Rates for Straight Trucks per 10^8 Miles

Trip Length	Model Year	Observed		Estimated	
		2 Axle	3 Axle	2 Axle	3 Axle
Over the road	Old	52.3	16.1	47.7	15.6
	New	49.3	17.0	53.3	17.4
Local	Old	167.9	44.7	204.7	37.1
	New	205.4	29.8	181.1	37.8

Overall Influence of Independent Variables

Number of Axles

The influence of this variable was prominent. In over-the-road service, 2-axle trucks showed approximately 3 times as high an accident rate as did 3-axle trucks. In local service, 2-axle trucks showed accident rates up to 6.5 times that for 3-axle trucks.

Trip Length

The influence of this variable was also important. For 2-axle trucks, over-the-road service showed a 3-4 times lower accident rate than did local service. For 3-axle trucks, the rate for over-the-road service was approximately one-half of those for local service.

Model Year

The influence of model year was negligible in over-the-road service, and was only moderate for 2-axle straight trucks in local service. This small influence of model year was similar to the combination-vehicle subset.

Straight Trucks Versus Combination Vehicles

Table 6 gives a comparison of the accident involvement rates for straight trucks and for singles and doubles. The table indicates the following:

1. In over-the-road service, straight trucks had the lowest overall involvement records. Their rates were considerably lower than those for most singles or doubles.
2. In local service, 3-axle straight trucks showed the lowest accident rate (38 involvements per 10^8 mi) of all truck types. On the other hand, van singles showed the highest accident rates in local service among all truck types.
3. Two-axle straight trucks showed a much higher accident rate than did 3-axle straight trucks. In general, the accident rates for straight trucks in over-the-road service were much smaller than those in local service. The difference was especially pronounced for 2-axle straight trucks where local service showed up to four times higher rates than did over-the-road service. A similar effect of trip-length was also observed for van singles and tanker singles.

Deductive Analysis

Combination-Vehicle Subset

The independent variables that were not considered in the causal model, due to the lack of the exposure data, were investigated by means of a deductive technique. The following list describes such variables:

1. Road class (undivided rural, divided rural, urban roads);
2. Day-night;
3. Loading status (empty or loaded);
4. Road surface condition (dry or wet-snowy);

TABLE 6 Comparison of Involvement Rates Among Truck Types

Trip Length	Model Year	No. of Axles	Straight Truck	Singles			Doubles		
				Van	Flat	Tanker	Van	Flat	Tanker
OR	New	2	53	73	46	39	159	242[a]	122
		3	17	97	111	103	90	133[a]	68[b]
	Old	2	48	66	64	79	114	–[c]	204
		3	16	105	172	99	58	343	39[a]
Local	New	2	181	200	99[a]	42[b]	193[a]	–[c]	–[c]
		3	38	580	108	258	–[c]	–[c]	–[c]
	Old	2	205	165	51	93[a]	70	–[c]	166[b]
		3	37	201	85	143	63[a]	70[b]	–[c]

Note: OR = over-the-road; the number of accident involvements is per 10^8 mi.

[a] Fewer than 15 accident involvements.
[b] Fewer than 5 accident involvements.
[c] Zero accidents and/or miles.

5. Driver age (18-30, 31-45, or 45+); and
6. Driver experience (less than 1 year, 1 year, 2-4 years, or more than 4 years).

These six variables are typically those for which the exposure is difficult to measure or obtain. To date, there is not a national exposure data set that contains such detailed information. The deductive analysis introduced here, therefore, also serves another purpose in that it demonstrates whether there is a strong need to add these variables in future data collection efforts for truck exposure.

In the deductive analysis, the effects of the five independent variables that had been found to be significant in the causal model were assumed to still hold true. This assumption was essential in order to assess whether the variable(s) under investigation would still be significant after having accounted for those five significant variables. If this variable was not significant, then the lack of the exposure information would not be as crucial to the understanding of accident involvements.

The deductive analyses of the preceding six variables were carried out based on the procedure described in the section entitled "Deductive Modeling." Only the summary results for the following groups of variables are reported here:

1. Road Class, Day-Night, and Road Surface Condition--There was a significant interaction effect on accident rates involving road class, road surface condition, and day-night. This interaction was important to the extent that the effect of day-night would not have been evident without the presence of the other two variables in the same analysis. In general, it was found that urban roads showed high accident rates for all trucks, especially during the day when the density of general road traffic was the highest. Doubles, more so than singles, often showed higher accident rates on undivided rural roads than on divided rural roads. Wet-snowy pavements raised the accident rates of all trucks on all roads. The road surface condition was found to accentuate the effect of day-night such that wet-snowy roads at night often had a particularly serious effect on singles and especially on doubles. Nighttime tended to affect doubles more than singles on divided rural roads. Daytime accident rates on urban roads and undivided rural roads were often high.

2. Driver Age and Driving Experience--The effect of driver experience and driver age was such that driver experience was found to be important in all (three) age groups considered. Driver experience appeared more critical for doubles than for singles, especially for 2-axle-tractor flatbed and tanker doubles. Drivers of doubles with 1 year or less of experience showed considerably higher accident rates than did drivers with over 4 years of experience. The influence of age was that younger ($\leq$30) and older drivers (45+), in general, showed higher accident rates than did 31 to 45-year-old drivers. Young drivers of tanker doubles showed higher accident rates than other drivers of the same vehicles.

3. Loading Status of Vehicle--The effect of loading status was also found to be important. In over-the-road service, most tanker singles and doubles showed lower accident rates when empty than when loaded. This was also true for flatbed singles and doubles.

Straight-Truck Subset

Deductive analyses were carried out to assess the influence of loading status and the interaction among road class, road surface condition, and day-night on accident rates of straight trucks (8). The results of these deductive analyses were as follows:

1. Most straight trucks had higher accident rates when loaded than when empty. This finding was similar to those for combination vehicles.
2. Wet-snowy conditions raised the accident rates of straight trucks on all roads, particularly the rates for 3-axle straight trucks. Wet-snowy conditions combined with night driving especially raised the accident rates of all straight trucks on all roads.
3. The effect of road class was that urban roads showed higher accident rates than did undivided rural roads, which, in turn, often showed higher rates than did divided rural roads under almost all environmental conditions. On urban roads, the accident rates at night were lower than those for daytime.

SUMMARY OF FINDINGS

The causal modeling indicated that the factors influencing the accident rates of large trucks and combination vehicles included vehicle configuration, trailer body style, trip-length, number of axles of power unit, and to a lesser extent, model year.

In over-the-road service, flatbed doubles had the highest accident rate followed by 2-axle-tractor tanker doubles, 2-axle-tractor van doubles, and 3-axle-tractor flatbed singles. In the other extreme, those with low accident involvements per mile were 3-axle straight trucks. Those with moderate involvements per mile included 2-axle straight trucks in over-the-road service, 3-axle-tractor tanker doubles in over-the-road service, and most 2-axle-tractor singles.

The deductive modeling revealed that road class, road surface condition, day-night, loading status, driver experience, and driver age were all significant predictors of accident rates. Of these, the most important variables were road surface condition, road class, loading status, and driver experience.

Wet-snowy pavements raised the accident rates of all trucks on all roads. The wet-snowy condition at night was especially hazardous. Urban roads were found to have higher accident rates than did rural roads for all trucks. Doubles usually showed a higher accident rate on undivided rural roads than on divided rural roads. The effect of loading status appeared to be more important for tankers and flatbeds than for vans. Tankers and flatbeds (singles or doubles) as well as straight trucks showed higher accident rates when loaded than when empty. Doubles, in particular, were found to be adversely affected more by less-than-favorable driving conditions than singles. These were conditions such as wet-snowy, undivided roads or nighttime driving.

The effect of driver experience appeared to be more prominent than driver age. Experience was found to be important for all three age groups considered. Drivers with less than 1 year of driving experience showed higher accident rates than did drivers with 2-4 years or over 4 years of driving experience. Driver experience appeared more critical for doubles than for singles, especially for 2-axle-tractor tanker and flatbed doubles. The following paragraphs summarize the findings on accident involvements and usage for straight trucks, singles, and doubles.

Straight Trucks

Straight trucks are not used as much as combination vehicles in interstate commerce. Their total annual mileage was less than 15 percent of that for van singles. Unlike combination vehicles, which are predominantly engaged in over-the-road service, straight trucks operated about equally in over-the-road and in local service. Both 2-axle and 3-axle straight trucks are used in over-the-road and in local service.

Straight trucks showed the lowest overall accident involvement rate among all truck types considered. In over-the-road service, their estimated involvement rates were one-sixth to two-thirds of those for most singles and van doubles. However, in local service, the involvement rate for 2-axle straight trucks was as high as those for most singles in local service. Factors that raised the involvement rate of straight trucks include the set-snowy condition, urban environments, undivided rural roads, and being loaded.

Analysis of accident type (8) indicated that approximately one-third of the accident involvements of straight trucks on rural roads were single-truck accidents; it was about one-fifth on urban roads.

Van Singles

Van singles are used far more extensively than any other truck type in interstate commerce and in the over-the-road operation. Approximately 80 percent of their annual mileage in over-the-road service was made by 3-axle-tractor van singles. Their mileage in local service was only 10 percent of that for over-the-road service.

The accident rate for 3-axle-tractor van singles in over-the-road service was similar to that for 3-axle-tractor tanker singles (approximately 100 involvements per 10^8 mi). Their accident rate was, on the average, approximately 30 percent lower than that for 2-axle-tractor van doubles. In local service, van singles showed a high accident rate (over 200 involvements per 10^8 mi).

Factors that raised the involvement rate of van singles include the wet-snowy condition, the wet-snowy condition at night, urban environments, and lack of driving experience. Van singles showed a higher involvement rate on wet-snowy divided rural roads than on wet-snowy undivided rural roads. On dry pavements during the day, their rate on undivided rural roads was higher than that on divided rural roads.

Flatbed Singles

Flatbed singles are used primarily in over-the-road service. The proportion of their annual mileage that was in local service was only 5 percent. Their annual over-the-road mileage was 25 percent of that for van singles. Most flatbed singles were operated by 3-axle tractors.

The involvement rate for 3-axle flatbed singles was higher than those for van singles and tanker singles (up to 170 involvements per 10^8 mi). The elements that raised their accident rate were the wet-snowy condition, urban environments, loaded flatbeds, and lack of driving experience.

Tanker Singles

Tanker singles are used primarily in over-the-road service. The proportion of their total annual mileage that was in local service was less than 5 percent. Their annual mileage in over-the-road was approximately 20 percent of that for van singles. Over 90 percent of tanker singles were operated by 3-axle tractors.

The accident rate for tanker singles in over-the-road service was similar to that for van singles (approximately 100 involvements per 10^8 mi). Their rate in local service was higher (150 to 250 involvements per 10^8 mi). Factors that raised the involvement rate of tanker singles include the wet-snowy condition, urban environments, loaded tankers, and lack of driving experience. Undivided rural roads showed a higher rate than did divided rural roads.

Analysis of accident types (8) revealed that for all empty singles on dry-pavement rural roads and on ramps, 20 to 40 percent of their total accident involvements were single-truck accidents. This proportion was higher, approximately 50 to 65 percent, for wet-snowy pavements. For loaded singles, the proportion of the total accident involvements that was single-truck accidents was approximately 50 to 65 percent on undivided rural roads and on ramps, and 30 to 50 percent on divided rural roads. Given similar roads and environmental conditions, loaded singles showed higher probabilities of single-truck accidents than did empty singles.

Doubles

(a) Van Doubles--Van doubles are used primarily in over-the-road service, which accounted for 95 percent of their total annual mileage. Approximately 80 percent of van doubles are operated by 2-axle tractors. The accident rate of 2-axle-tractor van doubles was approximately 115 to 160 involvements per 10^8 mi. Factors that raised the accident rate of van doubles include the wet-snowy condition, urban environments, undividued rural roads (during the day), and lack of driving experience.

(b) Flatbed Doubles--There were relatively few flatbed doubles in operation; their annual mileage was only 2 percent of that for van doubles and approximately 40 percent of that for tanker doubles. Their involvement rate was found to be the highest among all truck types that engaged in over-the-road service (up to 340 involvements per 10^8 mi).

Factors that raised their involvement rate include the set-snowy condition, the wet-snowy condition at night, urban environments, undivided rural roads (during the day), loaded doubles, lack of driving experience, and young and old drivers (less than 30 and over 45 years old).

(c) Tanker Doubles--Tanker doubles were used almost exclusively in over-the-road service. Two-axle-tractor tanker doubles showed an accident rate as high as 200 involvements per 10^8 mi. Their accident rate was higher than that for van doubles but lower than that for flatbed doubles. Factors that raised the involvement rates of tanker doubles include the wet-snowy condition, the wet-snowy condition at night, urban environments, undivided roads at night, loaded doubles, lack of driving experience, and young driver (less than 30 years old).

Analysis of accident type (8) indicated that for all doubles engaged in over-the-road service, approximately 40 to 50 percent of their total accident involvements on dry pavements was single-truck accidents. This proportion was higher, 70 percent, on wet-snowy pavements.

CONCLUSIONS

The findings in this paper were based on a discrete-multivariate analysis. The model used to analyze accident involvement rates was capable of quantifying both the independent (or main) effects and the interaction effects among all significant independent variables. Such a model, therefore, yielded estimates that were stable because the effects due to confounding variables were minimized.

The analyses conducted in this research indicate that, having adjusted for trailer style, trip length, model year, and number of axles of power units, most doubles and singles showed higher accident involvement rates than straight trucks.

In local operation and in the urban environments, van and tanker singles, as well as 2-axle straight trucks, indicated problems. The safety of singles on undivided rural roads and of 2-axle-tractor doubles should be further researched to find out why their accident rates were high. Countermeasures to reduce accident rates of all loaded combination vehicles, especially loaded tankers and flatbeds, should be investigated. Schemes aimed at increasing driver experience in operating combination vehicles, particularly doubles, are encouraged.

There is a strong need to improve the quality of the truck exposure data file so that information on variables such as road class, driver factors, region of the country where accident occurs, truck weight, load status, and loading practices can be made available. The future truck exposure data base should aim at obtaining a higher level of recording or measuring accuracy than that shown by the original TIU data base. Coverage in reporting truck accidents also needs improving and further research so that undercoverage biases, if they exist, may be reasonably identified. These shortcomings in the data bases can influence the findings of truck safety studies. All of the preceding information is vital to a better understanding of the accident experience of large trucks and combination vehicles.

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Truck Impact on Roadway Safety

ABISHAI POLUS and DAVID MAHALEL

ABSTRACT

A number of aspects connected with the operation and safety of trucks are discussed in this paper. The involvement rate of trucks in road accidents is found to be lower than that of passenger cars and buses; similarly, there is a decreasing trend in accident rate with an increase in gross vehicle weight. In contrast, the fatality rate in truck accidents is found to be higher than that involving passenger cars; also, a tendency exists toward an increase in the relative proportion of fatal accidents with an increase in gross vehicle weight. A multiplicity of injuries in truck-involved accidents is also noticed. It is concluded that the injury and fatality victims in such accidents are more likely to be the passengers and drivers of the other vehicles involved or pedestrians. Finally, a relatively high truck involvement is found in front-rear, side, and single-vehicle accidents.

Road accidents in which trucks are involved generally arouse great public interest and sensitivity, mainly because of their relatively high severity and the heavy economic damage accompanying them. In recent years, this sensitivity appears to have been heightened in light of the fact that trucks have been made larger and passenger cars smaller.

The relatively high severity of accidents involving trucks is a direct result of their basic characteristics, which, according to Neilson et al. (1) are as follows: (a) relatively large mass, resulting in instant velocity changes in smaller vehicles that strike them; (b) high rigidity of structure, resulting in most of the energy loss being dissipated in the collapse of the smaller vehicle; and (c) misalignment of structures, the height of truck structures resulting in damage to the upper and weaker parts of smaller vehicles.

Despite the high severity of truck accidents, the accident rate for trucks may be expected to be lower than that for passenger vehicles. Following are some of the reasons for this apparent anomaly:

1. Trucks record a relatively higher proportion of interurban mileage than do passenger vehicles, a determination that is particularly true for heavy trucks;
2. Trucks register much higher mileage, a fact that influences the creation of a low accident rate (the phenomenon of a low accident rate following high road exposure stems apparently from nonlinear relationships between accidents and exposure);
3. Truck drivers are generally more skilled in driving than are drivers of passenger cars; and
4. Vehicle maintenance of trucks, especially in the large companies, is generally stricter than that of passenger cars.

Despite the existence of a low accident rate for trucks, one may also point to the following reasons that would cause trucks to have a higher accident risk:

1. Driver fatigue: the driving time of truck drivers, both proportionally and in absolute terms, is higher than that of car drivers, and causes a decrease in driver attention span.
2. Structure and maneuverability: tires, brakes, braking distances, stability while braking, jackknifing possibility, power steering, and lashing of freight are among the characteristics creating a high accident risk for trucks.
3. Problems of overloading: the economic temptation to overload trucks creates a decrease in the safety factor of different truck parts.

The typical problems connected with the involvement of trucks in road accidents have been discussed in the literature. Eck (2) analyzed some 600 accidents related to runaway trucks and presented several contributing factors, among which were driver error, equipment failure, and lack of experience with mountain driving. A study by McGee et al. (3) on accident types and contributing factors indicated that truck-accident rates varied inversely with truck weight. Among the effects surveyed were those of roadway geometry, roadside features, and wide loads. A review of the research on truck size and weights by Freitas (4) concluded that the available research on the safety of large trucks is not congruent. One reason is that data in some studies are not consistent, particularly the mix between large combination-trucks, which tend to travel on rural freeways, and smaller single-unit trucks, which tend to travel on urban streets. Another reason is that the quality of the data is sometimes questionable because of the difficulty in calculating accident rates.

Lohman and Waller (5), who analyzed accident characteristics by vehicle weight, discovered that larger trucks were more likely to be involved in single-vehicle crashes than were cars or smaller trucks. Their study also suggested that some truck drivers appeared to encounter difficulties in stopping their vehicles; the use of improved braking systems, with greater braking power and less probability for failure, may therefore be considered as a possible remedy for truck accidents. This point was also discussed in Neilson (1), which is a study of accidents involving heavy-goods vehicles that further demonstrated that trucks, particularly when laden, take a considerably longer distance to stop than do cars.

This paper will deal with a number of aspects connected with truck operations, especially in the area of safety. The section that follows contains a discussion on the economic and safety implications of operating single versus double trailers. Succeeding sections make a detailed comparison between trucks and automobiles of accident rates, accident severity, and types of accidents.

One of the aims of the present work was to examine differences in safety performance among various gross vehicle weight (GVW) groups of trucks in Israel. For that reason, a new accident data file had to be constructed. This file was combined from two independent sources: the police accident file and the vehicle registration file. The latter was needed for supplying technical information concerning the vehicles (e.g., vehicle weight). The police accident file identified the vehicles involved in road accidents and provided more accident details.

LARGE-TRUCK COMBINATION OPTIONS

Long combinations of trucks have, for some time, constituted a subject of much controversy. Alongside the economic advantages of these vehicles (e.g., a saving in manpower), there exist doubts concerning the safety implications stemming from the use of combination trucks.

Polus (6) conducted an analysis of the operating costs of heavy-truck combinations in western Canada and evaluated their relative efficiencies. He found that because trucks operate under a variety of conditions, operating costs vary considerably, depending on the commodities carried, the service provided, and the operating conditions experienced. The parameters involved in determining these costs may be characterized as the internal and external factors of the trucking industry. Some of the internal factors include type of commodity; equipment, purchase, and maintenance policies; annual mileage traveled; and vehicle configuration. External factors include such variables as union rules and wage scales, road topography and surface type, climate, and payload and axle-weight limits.

The economic performance of any given truck combination can be compared to a 2-axle truck (or to any other base), and its relative value obtained. Figure 1 shows the relative economic performance of various heavy-vehicle combinations for a given annual mileage, based on payload-to-cost relationships, after comparisons were made with two types: a 2-axle truck (used as the base) and a 5-axle semi-trailer.

The 7-axle Rocky Mountain Double was found to be the most efficient combination--on the average, approximately 24.8 percent more efficient than the 5-axle combination. Similarly, 8-axle triple-trailer trucks were found to be, on the average, approximately 9.6 percent more efficient than semi-trailers.

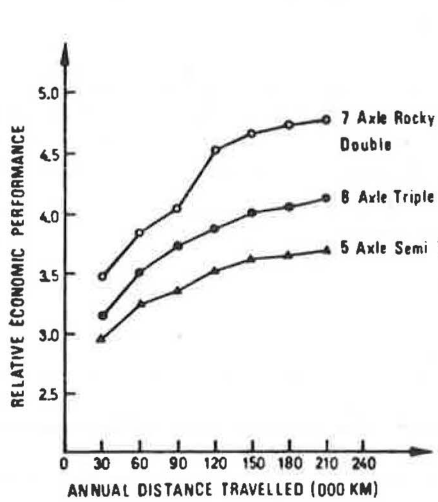

FIGURE 1 Relative economic performance of various heavy-vehicle combinations.

Various trucking companies had previously identified the 7-axle Rocky Mountain Double as the most suitable combination for long-distance freight movement. Company officials pointed particularly to the added flexibility of this type resulting from combining a short trailer with a regular 45-ft (13.6-m) trailer.

The literature contains conflicting evaluations of the safety of double trailers compared to singles. Thus, whereas Winfrey et al. (7) and Scott and O'Day (8) found that doubles have a relatively lower accident rate than do singles, Vallette et al. (9) offered the opposite conclusion. Figure 2, taken from this latter work, shows the accident rate per 100 million vehicle miles. In each weight group, the rate can be seen to be higher for double trucks than for singles. McGee et al. (5) on the other hand, found that the accident rate of the two truck types did not show a clear differentiation by itself. By contrast, in combined terms of distance and weight, double trailers showed a relative advantage in that the accident rate per 100 million ton-miles of travel was higher for the singles (14.7 versus 11.0 for the doubles). Peterson and Grull (10) analyzed the operations of triple-trailer combinations in comparison with doubles and singles during a 1-year field study in Utah. The accident data, though limited, indicated that triples were safer under the conditions in which they were operated.

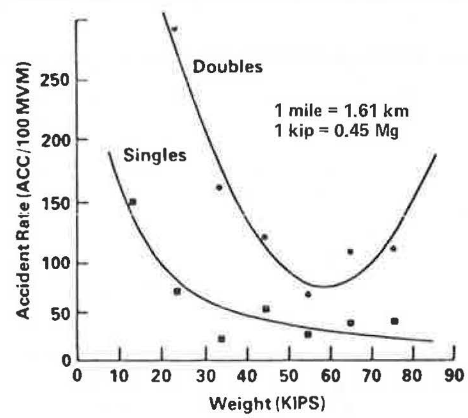

FIGURE 2 Accident rate per 100 million vehicle miles.

Freitas (4), in his review of accident research, gave this evaluation: "It does seem clear that larger and heavier trucks can be operated safely--but under certain conditions, larger trucks do have real safety problems." One of these problems, especially for combination trucks, is presented by an empty vehicle. The extent of the proneness to accident involvement of empty trucks varies from company to company, according to the relative proportion of trips without freight. Indeed, in large companies in which the number of trips without freight is minimal, no differences in accident rate were found between single and combination trailers.

The conclusion to be derived from the facts presented in this section is that in light of the economic advantages inherent in combination trailers, the correct way must be found to operate these trucks such that their alleged safety disadvantages will be minimized. In view of the heavy weight and technological complexity of such trucks, the following elements are necessary: (a) a high level of driver skill; (b) a high level of vehicle maintenance; and (c) an avoidance of trips without freight or, alternatively, the development of appropriate technology for empty-truck transport.

EFFECT OF TRUCK WEIGHT ON ACCIDENT INVOLVEMENT

The various weight groups of the single-unit truck represent a wide range of weight-related mechanical problems and of technologies intended to overcome these problems (number of axles, types of brakes, etc.). Figure 3 shows the road-accident involvement of various weight groups of trucks in Israel. The parameter of road-accident involvement is the average number of accidents per million kilometer of travel for the years 1979-1981. In addition, the accident-involvement rates of passenger vehicles (cars and buses) are presented for comparison. The criteria for defining an accident were the same for cars, trucks, and buses: by law, an accident must be reported to the police whenever it involves an injury or a fatality; it may be reported when it involves only property damage. An accident is counted as such only when reported to the police. Data on this subject indicate the following characteristic trends: (a) passenger cars and buses have a higher accident-involvement rate than any truck weight group; and (b) the accident rate decreases with gross truck weight.

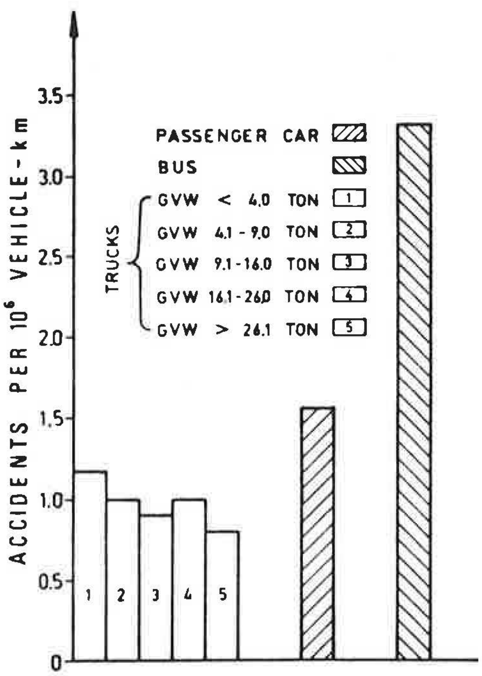

FIGURE 3 Road accident involvement of various weight groups of trucks in Israel.

The first trend also exists in other countries. Wolf (11) found that in respect to general accident-involvement rate, the truck system has the best safety record: 1,510 accidents per 100 million vehicle miles, compared with 3,000 for cars and 4,310 for buses. Vallette et al. (9) also found that the accident rate changes inversely with truck weight and that this tendency occurs both for single- and double-unit trucks. Accident statistics from Canada based on the Provincial highway system and data base of Saskatchewan, are given in Table 1 and offer the following principal features:

1. The accident rate for large semi-trailers and trailers (5 axles or more) is lower than the rate of accidents either for passenger cars or for all other categories of vehicles.

2. The rate of accidents for passenger cars is lower than that for pickup vehicles.

3. The 3-axle, semi-trailer (power units only or small trailers) has the highest accident rate of all vehicles. This indicates, perhaps, careless driving, compounded by possible speed-limit violations and lack of stability.

4. The rate of accidents for single-unit trucks is higher than that for 5 or more axles, but lower than the rate for passenger cars.

TABLE 1 Number and Rate of Accidents on the Provincial Highway System in Saskatchewan, Canada, by Type of Vehicle, in 1980

Type of Vehicle	Estimated 1980 Highway Travel: Total Highway Travel (km: 10^6)	Estimated 1980 Highway Travel: Percent of Total Highway Travel	Accidents[a]: Total	Accidents[a]: Total (%)	Accident Rate (accidents per 10^6 vehicle km)
Passenger cars	3,061.05	57.9	4,321	54.9	1.412
Pickups[b]	1,501.45	28.4	2,360	30.0	1.572
Single-unit trucks	243.19	4.6	309	3.9	1.271
Semi-trailers:					
3-axle combinations	15.86	0.3	118	1.5	7.440
5 or more axles	380.65	7.2	409	5.2	1.074
Others[c]	63.44	1.2	295	3.8	4.650
Total[d]	5,286.79	100.0	7,864	100.0	

[a]Includes fatal, injury, and property-damage accidents.
[b]Includes all panels of light trucks with single wheels on rear axle.
[c]Includes emergency vehicles, construction equipment, motorcycles, farm equipment, motor homes, snowmobiles, and buses.
[d]Totals may not sum due to rounding.

It is possible to distinguish in statistics from South Africa, as in data from Israel, the United States, and Canada, that the accident rate for passenger cars is higher than that for trucks. Accident involvement data on South African roads are given in Table 2. As can be seen, the rate in 1981 for petrol and diesel trucks was 7.14 and 9.71 accidents per million km, respectively, whereas the accident rate for passenger cars was 15.19 per million km.

The distinction between truck groups correlates with the type of engine (e.g., the petrol engine characterizing lighter trucks, and the diesel engine of the heavier vehicles). It should be noted that there is an extensive weight group (up to 12 tons inclusive) of trucks that can be equipped with either petrol or diesel engines. The fact that the South African data show the accident-involvement rate of diesel-driven trucks to be higher than that of petrol-driven vehicles indicates the possibility that heavy vehicles in that country are involved in more accidents than are light trucks.

In summary, it may be said that despite the physical dimensions and the technological problems of heavy vehicles, it is not possible to point to a higher accident involvement with an increase in the dimensions and weight of trucks. On the contrary, there is much evidence that the accident rate for trucks is lower than that for passenger cars, and that there is a decreasing trend in accident rate with an increase in GVW.

EFFECT OF TRUCK WEIGHT ON ACCIDENT SEVERITY

The weight of a truck involved in a road accident constitutes a significant factor in the severity of

TABLE 2 Accident Involvement on South African Roads

	1980			1981		
Vehicle Type	Total Travel (million km)	Total Accidents	Accident Rate	Total Travel (million km)	Total Accidents	Accident Rate
Motor cars, station wagons, and taxis	28,784	385,570	13.39	29,731	451,576	15.19
Light trucks (petrol-driven)	9,982	62,178	6.22	10,424	74,390	7.14
Heavy trucks[a] (diesel-driven)	4,033	32,840	8.14	4,282	41,564	9.71

[a]Includes single-unit and articulated vehicles.

the accident because of the effect of a heavy mass on the speed change of the vehicle that crashes with the truck. Figure 4 shows the percentage of fatal accidents of the total number of accidents in which trucks of a certain weight group were involved. For comparison, statistics are also presented for passenger cars and buses. The principal finding is a rise in the relative proportion of fatal-accident involvement with an increase in truck weight. In other words, the heavier the truck, the more the risk grows that when the truck is involved in an accident, it will be a fatal one. In addition, the relative proportion of fatal accidents in which trucks were involved is higher than that in which passenger vehicles were associated.

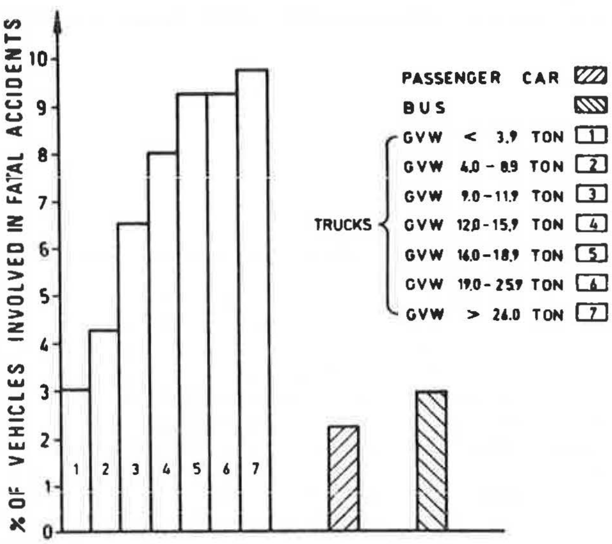

FIGURE 4 Percentage of fatal accidents of the total number of accidents involving trucks of a particular weight.

The increasing risk of a fatal accident with vehicle weight increase is expressed, also, in the overall probability of such an accident with each kilometer traveled. Figure 5 shows the rates of fatal accidents involving trucks, passenger cars, and buses. A trend can be discerned of an increase in fatal-accident involvement with an increase in truck weight. It should be noted that the involvement rates of trucks are higher than those of passenger cars but lower than those of buses.

Another parameter reflecting accident results is the average number of injuries per vehicle involved in an accident. Figure 6 shows these rates for trucks, buses, and passenger cars. As can be seen, except for the 4.0- to 8.9-ton weight group, the average number of injuries occurring in truck-involved accidents is greater than that of passenger cars and buses. In addition, then, to the fatal nature of truck accidents, there is an aspect of a multiplicity of injuries in truck-involved accidents. This phenomenon is all the more striking in view of the fact that the number of passengers in a truck is generally lower than in any other vehicle.

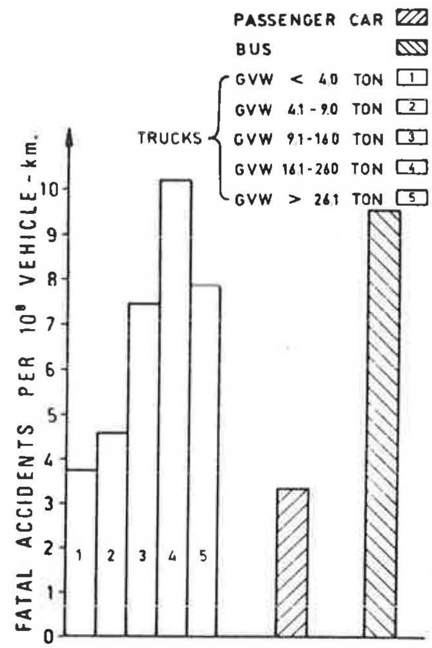

FIGURE 5 Rates of fatal accidents involving trucks, passenger cars, and buses.

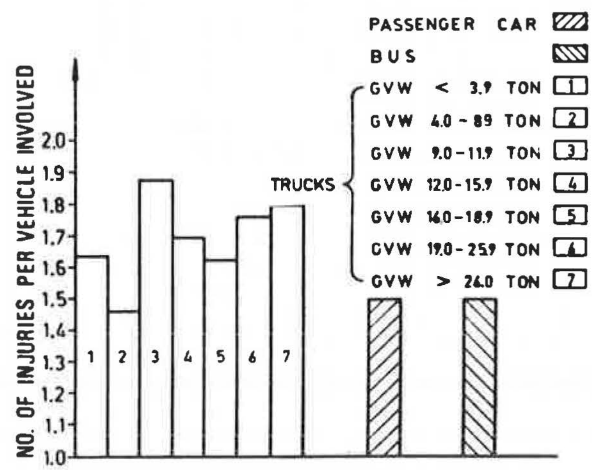

FIGURE 6 Injury rates for trucks, buses, and passenger cars.

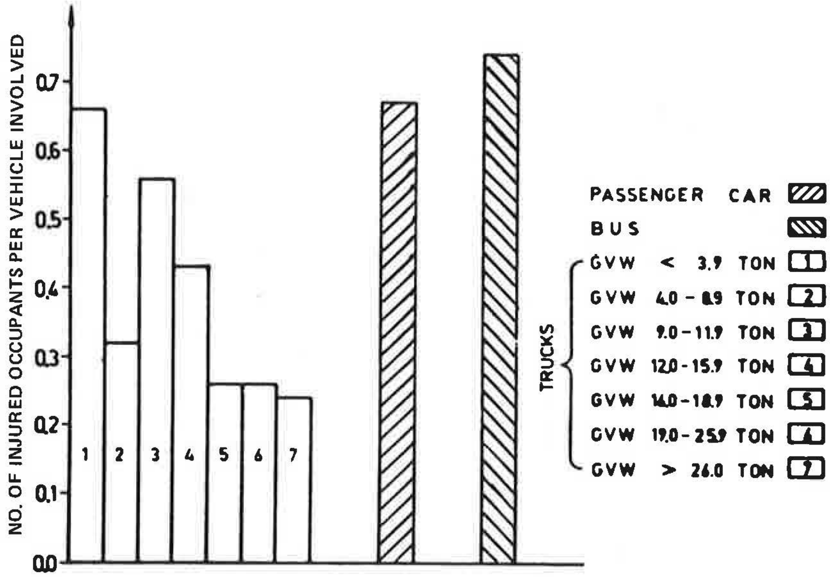

FIGURE 7 Average number of occupants per 1,000 vehicles involved in accidents, by vehicle type.

It may be concluded that the injuries and fatalities are passengers and drivers of the other vehicles or pedestrians.

To examine this phenomenon in more detail, a calculation was made of the average number of vehicle occupants injured per 1,000 vehicles involved in accidents, according to the type of vehicle in which the injured person was riding. Figure 7 shows these data. It can be seen that more car and bus occupants than truck riders are injured. Similarly, the heavier the weight of the truck, the smaller the number becomes of injured truck occupants. These facts highlight the protection that the truck affords its driver and passengers. As mentioned, however, there is a greater chance of the truck's injuring, and injuring more severely, other road users.

GEOGRAPHICAL DISPERSION OF ACCIDENTS

The geographical dispersion of road accidents in which trucks are involved is said to coincide, on the one hand, with the roads on which trucks have great exposure and, on the other hand, with the areas at which they meet with typical problems. In accordance with these two influences, one can expect a relatively high percentage of truck accidents to take place on the upgrades, interchanges and intersections, curves, and downgrades of interurban roads.

Despite the fact that there are no exact statistics reflecting the mileage distribution of trucks between urban and nonurban roads, it is reasonable to assume that the heavier the truck, the greater its relative mileage proportion outside the urban area. Accordingly, an increase may be expected in the relative proportion of accidents on interurban roads with the increase in truck weight.

Figure 8 shows the breakdown of accidents on interurban roads in Israel according to various truck weights. As might have been expected, the accident percentage rises with the increase in truck weight. In each weight group, moreover, the relative proportion of accidents is higher for trucks than for passenger cars and buses. The relatively high percentage of accidents in interurban areas may explain some of the severity of accidents involving heavy vehicles. As is well known, interurban roads are characterized by higher travel speeds, leading to more severe accidents, than urban roads.

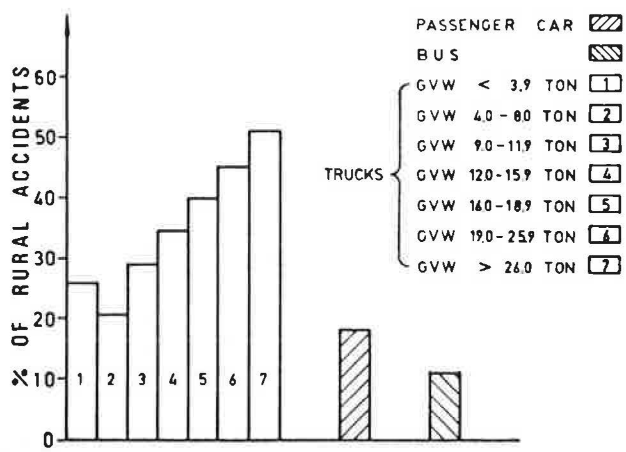

FIGURE 8 Breakdown of accidents on interurban roads in Israel according to various truck weights.

The high risk of truck accidents at intersections and interchanges stems from the long stopping distances of trucks, their difficulty in maneuvering in small radii, and their inability to develop high accelerations. Indeed, Vallette et al. (9) reported that 16 percent of truck accidents take place in the area of interchanges. Figure 9 shows the percentage of accidents at interurban intersections in Israel of the total number of interurban truck accidents, according to various weight groups. From these data, however, no trend or greater tendency to accidents at intersections can be distinguished for trucks relative to other types of vehicles.

TYPES OF ACCIDENTS

The characteristic problems of trucks expose them to certain types of accidents. One of the most common types of accidents in which a high truck involvement may be expected is the rear-end collision. Figure 10

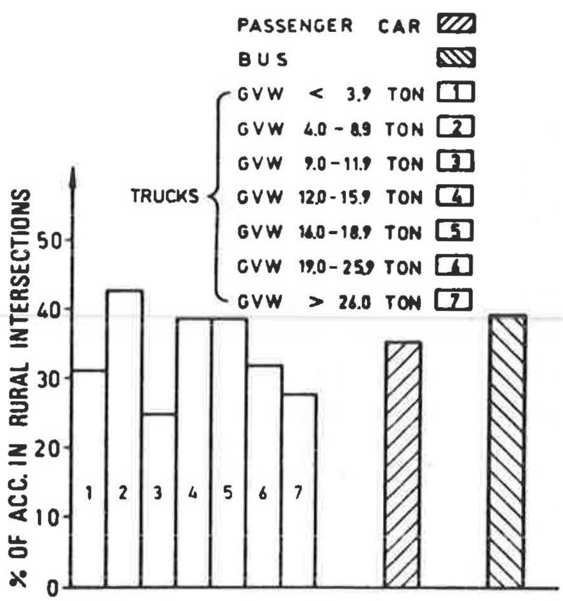

FIGURE 9 Percentage of accidents at interurban intersections in Israel.

shows the distribution of the types of accidents in Israel in which trucks were involved from 1979-1982. As can be seen, all categories of rear-end accidents account for as much as 35 percent of all truck-involved accidents. Trucks are exposed to this type both at intersections and on grades. At intersections, the problem stems from the stopping difficulties of trucks. On upgrades, trucks are prone to being rear-ended by overtaking vehicles; on downgrades, a truck may rear-end a slower-moving vehicle. Another type of accident in which one may expect a high involvement of trucks is a side-to-side collision. These are created on account of the dimensions of trucks and their special difficulties on curves.

As can be seen from the data shown in Figure 10, heavy vehicles are involved in relatively more rear-end collisions, and single-vehicle accidents than are passenger cars. The high involvement of buses in single-vehicle accidents stems from injuries to passengers while boarding or alighting or to inside passengers as a result of the sudden braking of the bus.

SUMMARY AND CONCLUSIONS

This paper has discussed a number of aspects connected with the operations and safety of trucks, the

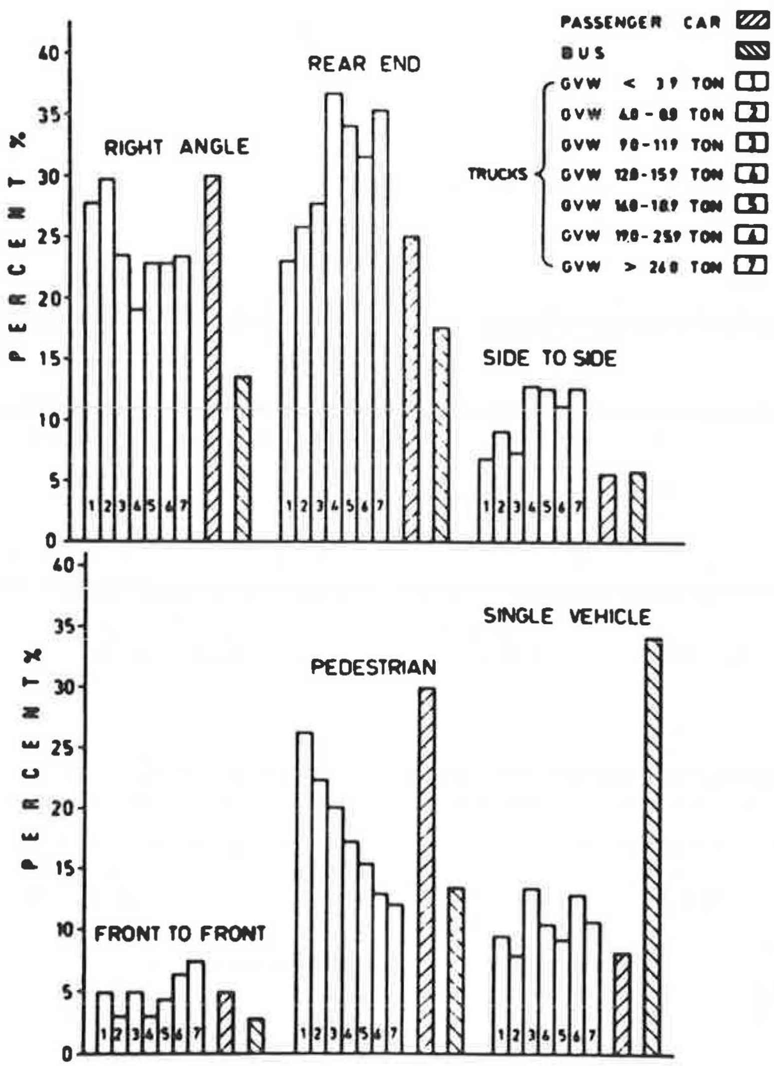

FIGURE 10 Distribution of type of truck accident in Israel from 1979 to 1982.

accidents involving which are associated with heavy economic damage and severity. As a direct result of their weight, structure, and operational characteristics, trucks were seen to be prone to certain types of road accidents--front-rear, side, and single vehicle--on certain geographical elements of the road such as intersections, grades, and curves.

From the data that were processed and surveyed for this study, the following conclusions may be drawn:

1. Long combination trucks, such as doubles and triples, have economic advantages over single-unit trucks; the advantage is expressed in indices of relative economic efficiency;
2. There are conflicting evaluations of the safety of double and triple trailers compared to singles, although most studies suggest that longer combinations have good safety records;
3. In relative terms of involvement (accidents per million kilometer of travel), passenger cars and buses are involved in more accidents than are trucks;
4. A decreasing trend in accident rate exists with increasing GVW;
5. An accident in which a heavy truck is involved will, in all probability, be more fatal than an accident involving a light truck;
6. The number of injuries in an accident involving a truck is greater than in accidents in which no trucks are involved. On the other hand, injuries to truck occupants are lower than they are to passengers in cars and buses; further, there exists a decreasing injury tendency with GVW. Specifically, when trucks are involved in an accident, the victim is more likely to be someone other than the truck driver;
7. The heavier the weight of a truck, the greater the relative proportion of interurban accidents in which it is likely to be involved; and
8. Relative to passenger cars, trucks are involved in more front-rear, side, and single-vehicle-type accidents.

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Analysis of the Effect of Bumper Involvement Criteria on Evaluating Bumper Performance

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ABSTRACT

The analysis of insurance claim data has been an important technique used to assess the effectiveness of federal standards for automotive bumpers. Studies assessing each version of these standards since their inception in 1973 have used this technique. The identification of bumper-involved claims is an essential requirement in performing such studies. Recent changes in automotive design have complicated the process of identifying bumper involvement. Examined in this paper are several different damage criteria that are currently applicable toward identifying bumper-involved insurance claims. The implications of each of these criteria in influencing the results of claim analyses are presented. In addition, a new cost-effectiveness measure, E, which is the product of insurance claim proportion and the average repair cost of these claims, is developed to quantify the risk or expected expense of repairing a vehicle in the first year of ownership due to a low-speed accident. The usefulness of this measure in performing insurance claim analyses is demonstrated.

Federal Motor Vehicle Safety Standards are periodically selected for review. These reviews are designed to determine whether these standards are

1. Resulting in the reduction of accident frequency and injury severity;
2. Leading to benefits commensurate with the costs of complying with the standard; and
3. Not imposing unnecessary burdens on the economy, individuals, public or private organizations, or state and local government.

The bumper standard enacted by NHTSA is one of the standards that has been under continuing review.

This paper contains a description of an analysis of the performance of automotive bumpers designed to conform to NHTSA's standards for exterior protection for 5-mph impacts (1). This version of the standard was in effect for vehicles manufactured in model years 1980 through 1982. The analysis was performed by examining insurance claim data for these model years, and represents an extension of previous analyses (2-4) of the effectiveness of bumpers in minimizing crash damage. The previous analyses, made by KLD Associates, Incorporated, under contract to NHTSA, considered pre-1972, 1973, 1974-1978, 1979, and 1980 versions of the bumper standards. These analyses, and others [summarized by NHTSA (5)] showed the benefits of various versions of the bumper standards. Similar results were obtained in a study by the Highway Loss Data Institute (HLDI) in which a different data base was used (6).

In light of NHTSA's decision to modify the bumper standard from 5 mph to 2.5 mph effective with 1983 model year vehicles (7), this study provides a framework for examining the impacts of the newer 2.5 mph standard. In this study, the groundwork is laid for such an evaluation by providing a detailed assessment of the effects of the pre-1983, 5-mph standard.

The research contained in Abramson and Yedlin (1) examines the effects of many different factors on bumper performance. This paper focuses on how the damage criteria used to identify bumper involvement influences the evaluation of bumper performance. (Note: Data for this study were obtained from the State Farm Insurance Companies and represent a nationwide sample of insurance claims from their claim service centers.)

EXPERIMENTAL DESIGN

The aggregate sets of claims available for model years 1980-1982 were examined. Only claims involving 1-year-old vehicles where bumpers were either repaired or replaced were considered. An experiment was designed to address two issues: (a) whether there were any significant differences in the available aggregate claim data between model years, and (b) how the criteria used to identify bumper-involved claims influence the understanding of the data.

Two measures of effectiveness were employed to understand each of these issues. These included: (a) the proportion of property damage claims involving bumpers, and (b) the average repair cost of these claims. A cost-effectiveness measure, E, which is the product of the proportion of property damage claims and the average repair cost of these claims is also utilized in the analysis.

The two criteria used to identify bumper-involved claims included repair or replacement of (a) only the bumper face bar, and (b) either the face bar or the bumper fascia or both. The format of the data available for 1980 allowed consideration of the first criteria only. The 1981 and 1982 data permitted both criteria to be considered. Claims for each model year were stratified into four market classes: subcompact, compact, intermediate, and full size, and two impact points: front and rear.

For the proportion analysis, the number of front and rear bumper claims were aggregated for each market size class and for each model year period. The proportion of these claims, relative to the total of all property damage claims for that market class, was computed for each model year. No totaled vehicles were in the State Farm data, although both collision and liability claims were included. For each of the time-period comparisons (1980 versus 1981, 1981 versus 1982, and 1980 versus 1982), the hypothesis test for differences in proportions was computed for each market class-impact point combination.

In total, four separate statistical comparisons were performed for the proportion analysis including (a) three model year comparisons using face bar damage as the involvement criteria, and (b) one comparison between the 1981 and 1982 data using face bar or fascia damage as the involvement criteria.

The same four statistical comparisons were performed for the analysis of average repair costs. In each case, the average repair cost was computed for each market class-impact point combination. The differences between average costs were statistically tested using the hypothesis test for the difference between means at a 5 percent confidence level.

PROPORTION ANALYSES

The results of the four statistical comparisons performed on bumper claim proportions are given in Table 1. This table gives the bumper claim proportions stratified by impact point and market class. Significant differences at the 5 percent confidence level are indicated. This table depicts comparisons of all available data for model years 1980-1982 examining both criteria for bumper involvement. Available sample sizes are given in Table 2.

Employing only face bar damage to identify bumper-involved claims, the table indicates no significant differences in the proportion of these claims between 1980 and 1981. Between 1981 and 1982, a significant reduction is noted for subcompact vehicles for both front and rear impacts. This reduction is also noted for the vehicle classification "All Classes" for 1981 and 1982 claims. This is

TABLE 1 Summary of Claim Proportion Analyses

Vehicle Size and Involvement Criteria	Model Year	Claims by Vehicles of Designated Size (% of total)		Total Bumper-Related Accidents
		Front	Rear	
Subcompact vehicles				
Face bar	1980	21.2	11.5	32.7
	1981	20.7	10.1	30.8
	1982	16.0[a,b]	7.2[a,b]	23.1[a,b]
Face bar-fascia damage	1981	28.1	13.5	41.6
	1982	31.1[b]	14.0	45.1
Compact vehicles				
Face bar	1980	21.5	14.8	36.2
	1981	22.2	13.7	35.9
	1982	23.0	12.1[a]	35.1
Face bar-fascia damage	1981	29.0	16.4	45.4
	1982	32.4[b]	15.7	48.1
Intermediate vehicles				
Face bar	1980	25.5	14.4	40.0
	1981	22.4	17.6	40.0
	1982	23.0	17.4	40.4
Face bar-fascia damage	1981	23.1	18.4	41.6
	1982	24.0	18.5	42.5
Full-size vehicles				
Face bar	1980	23.4	21.9	45.3
	1981	22.7	18.0	40.6
	1982	21.0	17.4	38.0
Face bar-fascia damage	1981	22.7	18.8	41.4
	1982	20.7	17.4	38.0
All classes				
Face bar	1980	21.7	13.0	34.8
	1981	21.4	12.2	33.7
	1982	17.9[a,b]	8.8[a,b]	26.8[a,b]
Face bar-fascia damage	1981	27.8	15.1	42.9
	1982	31.0[b]	14.6	45.6[b]

[a]Difference in claim proportions relative to 1980 claims is significant at a 5 percent confidence level.
[b]Difference in claim proportions relative to 1981 claims using same involvement criteria is significant at a 5 percent confidence level.

no doubt due to the predominance of subcompact vehicles in the sample. The reduction in subcompact and All Classes claim proportion is also noted between 1980 and 1982. In addition, a significant reduction is shown for rear impacts of compact vehicles.

The reduction in subcompact claim proportion suggests differences in bumper design over the 1980-1982 period, particularly between 1981 and 1982 model year vehicles. Newer soft-face designs often employ a soft-cover (fascia) over the bumper face bar. These exterior surfaces are included within the bumper standards. By considering damage to the face bar only, claims involving damaged fascia without face bar damage are ignored. Only the more severe claims involving both fascia and face bar damage would be considered. If one hypothesizes an increase in the proportion of vehicles using soft-face designs in the 1982 sample, the face bar damage criteria would likely identify a smaller proportion of 1982 bumper damage.

Using a revised criteria in which bumper involvement implies damage to the face bar and/or fascia parts, the data in Table 1 indicate an increase in front-impact claim proportions for subcompacts and compact vehicles between 1981 and 1982. Again, the predominance of these market classes in the sample produces the same results for All Classes.

The two criteria for bumper involvement produce opposite results. This tends to strengthen the suspicion that the proportion of vehicles with hard and soft face designs differs between the 1981 and 1982 samples.

It appears that considering only face bar damage would result in an underestimation of the bumper involvement for 1982 vehicles. Considering face bar or fascia damage suggests the possibility that newer soft face designs may actually increase bumper involvement. Due to new soft-cover designs, either of these two criteria may overstate bumper involvement relative to the bumper protection standards. This occurs because the standards are expressed in terms of exterior damage. In some bumper designs, an air gap exists between the fascia and the face bar. An impact might be imparted to damage the face bar but the fascia may rebound to its original shape. As an exterior standard, no damage would be observed and such impacts would pass the standard. However, since the face bar was damaged, a claim for such an impact would be considered as bumper-involved by either the face bar or face bar-fascia damage criteria used in this study.

To more closely reflect the bumper standards, more detailed criteria would be needed. This exterior damage criteria would consider only fascia damage for soft cover designs and only face bar damage for traditional designs. However, for purposes of analyzing the factors influencing bumper performance, the criteria utilized by this study are considered more appropriate.

REPAIR COST ANALYSES

Table 3 gives the comparisons performed on average repair costs. This table is presented in a format similar to that employed for the proportion analyses in Table 1.

Table 3 gives the cost comparison for the model-year claim data available from 1980 through 1982. Costs for claims using both the face bar and face bar-fascia damage criteria for bumper involvement are presented. All costs are presented in 1982 dollars and adjusted for inflation.

Using only the face bar criteria, the data in Table 3 indicate that intermediate vehicles experienced a significant increase in average repair costs

TABLE 2 Sample Sizes for Proportion and Repair Cost Analyses

Vehicle Size and Involvement Criteria	Model Year	Sample Sizes Front	Sample Sizes Rear	Total Bumper-Related Accidents	All Claims
Subcompact vehicles					
Face bar	1980	578	315	893	2,730
	1981	1,021	501	1,522	4,934
	1982	914	410	1,324	5,722
Face bar-fascia damage	1981	1,388	666	2,054	4,934
	1982	1,779	802	2,581	5,722
Compact vehicles					
Face bar	1980	288	198	486	1,341
	1981	688	424	1,112	3,099
	1982	424	224	648	1,847
Face bar-fascia damage	1981	899	508	1,407	3,099
	1982	599	289	888	1,847
Intermediate vehicles					
Face bar	1980	108	61	169	423
	1981	216	170	386	966
	1982	66	50	116	287
Face bar-fascia damage	1981	224	178	402	966
	1982	69	53	122	287
Full-size vehicles					
Face bar	1980	32	30	62	137
	1981	29	23	52	128
	1982	25	21	46	121
Face bar-fascia damage	1981	29	24	53	128
	1982	25	21	46	121
All classes					
Face bar	1980	1,006	604	1,610	4,631
	1981	1,954	1,118	3,072	9,132
	1982	1,429	705	2,134	7,977
Face bar-fascia damage	1981	2,540	1,376	3,916	9,132
	1982	2,472	1,165	3,637	7,977

for front-impact claims between 1980 and 1981. However, this may be a statistical aberration because costs in 1982 are similar to those in 1980. No other significant changes are noted in Table 3 throughout the period between 1980 and 1982. This is true not only in aggregate but for each market class and impact point regardless of the criteria used to determine bumper involvement.

TABLE 3 Summary of Repair Cost Analyses

Vehicle Size and Involvement Criteria	Model Year	Average Repair Costs at 9.36% Inflation Rate (1982 dollars) Front	Rear	Average All Bumper-Related Accidents
Subcompact vehicles				
Face bar	1980	1,365	874	1,191
	1981	1,368	934	1,225
	1982	1,388	951	1,253
Face bar-fascia damage	1981	1,332	897	1,184
	1982	1,299	883	1,170
Compact vehicles				
Face bar	1980	1,349	844	1,144
	1981	1,384	859	1,184
	1982	1,387	959	1,239
Face bar-fascia damage	1981	1,317	839	1,144
	1982	1,307	911	1,178
Intermediate vehicles				
Face bar	1980	1,289	907	1,151
	1981	1,566[a]	1,035	1,331[a]
	1982	1,361	985	1,199
Face bar-fascia damage	1981	1,550	1,050	1,328
	1982	1,373	993	1,207
Full-size vehicles				
Face bar	1980	1,959	1,242	1,612
	1981	2,568	1,048	1,882
	1982	1,901	1,266	1,611
Face bar-fascia damage	1981	2,568	1,044	1,864
	1982	1,901	1,266	1,611
All classes				
Face bar	1980	1,371	886	1,189
	1981	1,413	923	1,234
	1982	1,396	966	1,253
Face bar-fascia damage	1981	1,354	898	1,193
	1982	1,309	902	1,178

[a]Difference in claim costs relative to 1980 claims is significant at a 5 percent confidence level.

COST-EFFECTIVENESS MEASURE

To obtain a measure of the relative cost-effectiveness of the 1980, 1981, and 1982 bumpers, the following figure of merit has been derived. For any given stratification S, let N_S represent the total number of vehicles in that strata for a given year. The product $P \times C \times N_S$, where P is the proportion of vehicles of type S reporting a bumper-involved accident and C is the average cost per vehicle of Type S to repair the resulting damage, represents an estimate of the total cost of repairing vehicles of type S that have been involved in bumper accidents for the given year. Normalizing this total cost over all vehicles in strata S yields:

$$E = (P \times C \times N_S = P \times C)/N_S$$

where E represents a measure of cost-effectiveness or risk, in dollars, associated with stratification S. In other words, E represents the repair cost for bumper-involved accidents averaged over all vehicles, N_S, in stratification S. This value E can then be interpreted as a measure of the risk the owner of a vehicle of type S assumes in terms of the anticipated expense of repairing the vehicle in the first year of ownership due to a low-speed accident. Equivalently, E can be considered a figure of merit for the cost-effectiveness of the automobile bumper for a given stratification.

Table 4 gives the claim proportions, average cost values, and computed cost-proportion product E for the All Classes aggregate for 1980, 1981, and 1982. These tables stratify results for both the face bar damage and face bar-fascia damage criteria. The tables further stratify results for front impacts, rear impacts, and the combination of front and rear impacts.

TABLE 4 Comparison of 1980, 1981, and 1982 Data Using Cost-Proportion Product E for All Classes

Model Year	Proportion	Cost ($)	E = Prop. x Cost
Face Bar Only (all classes combined)			
1980	.3477	1,189	413.42
1981	.3364	1,234	415.12
1982	.2675[a]	1,253	335.18
Face Bar Only (all classes, front)			
1980	.2172	1,371	297.78
1981	.2140	1,413	302.38
1982	.1791[a]	1,396	250.02
Face Bar Only (all classes, rear)			
1980	.1304	886	115.53
1981	.1224	923	112.98
1982	.0884	966	85.39
Face Bar-Fascia (all classes combined)			
1981	.4288	1,193	511.56
1982	.4599[a]	1,178	537.05
Face Bar-Fascia (all classes, front)			
1981	.2781	1,354	376.55
1982	.3099[a]	1,309	405.66
Face Bar-Fascia (all classes, rear)			
1981	.1507	898	135.32
1982	.1460	902	131.69

[a]Indicates significant figure.

From the first half of Table 4, which contains data on face bar damage only, the measure E indicates that no substantial change in effectiveness occurred between 1980 and 1981 in either front or rear impacts; however, a substantial decrease in E of approximately $80 occurs in 1982 for the combined front and rear cases. Most of this decrease, $50, is due to a decrease in E for front impacts with the remaining $30 decrease due to a decrease in E for rear impacts. Considering only face bar damage, the measure E suggests that the 1982 bumpers are more cost effective than those in either 1980 or 1981. It was also suggested earlier that the face bar damage criteria may underestimate 1982 claim involvement. This is borne out by comparing face bar-only results for E against face bar-fascia damage results. The value of E for the latter is increased by approximately $100 (front and rear impacts combined) for 1981, and by approximately $200 for 1982. Thus, when fascia damage is included in the criterion, more costly accidents are included in the sample, that is, fascia damage introduces accidents that result in costly damage, even though the face bar itself does not require repair or replacement.

Table 4 (d,e,f) gives data indicating that the value of E for all impacts has increased from 1981 to 1982 by approximately $25 entirely because of an increase in E for front impacts. Thus, this definition of bumper involvement leads to the conclusion that the 1982 bumpers are, overall, less cost effective than those in 1981.

Two important conclusions can be drawn from this analysis. First, considering only face bar damage to identify bumper-involved accidents appears to result in a substantial underestimation of the repair cost effectiveness of the bumper. Furthermore, this underestimation becomes more pronounced with the changes in design occurring from 1981 to 1982. Thus, it is apparent that the face bar-fascia damage definition is the appropriate one to use to properly assess bumper effectiveness in the future.

Based on this first conclusion, it appears that the 1982 bumpers are less cost effective than the 1981 bumpers. The observed increase of $25 in E from 1981 to 1982 for all impacts represents a 5 percent increase over 1981. It should be pointed out that these results are based on the observed values and have not been tested for statistical significance.

Table 5 contains data on the computed value of E by market class and year for both the face bar and face bar-fascia damage definitions. In general, the value of E increases with vehicle size. Also, as noted previously, E is greater when considering face bar or fascia damage, than only face bar damage.

Subcompacts, constituting a major portion of the total mix, exhibit the same results as shown in the previous section for the year-to-year comparison using the vehicle aggregate. Thus, the face bar criteria indicate a decrease taking place from 1981 to 1982, however, the fascia-face bar data show an increase from 1981 and 1982. In each case, the change in E primarily reflects changes for front impacts.

For compacts, however, both involvement criteria show an increase in E from 1980 to 1982. The face bar data show a $10 increase in E from 1981 to 1982 ($424 to $434) for all impacts combined, whereas, the face bar-fascia damage comparison shows an increase of approximately $50 ($519 to $566) from 1981 to 1982. Thus, the inclusion of fascia damage in-

TABLE 5 Value of Cost-Proportion Measure E by Market Class and Year

Market Class and Model Year	Bumper Involvement Definition					
	Face Bar Only			Fascia-Face Bar		
	Front	Rear	Combined	Front	Rear	Combined
Subcompact						
1980	288.97	100.86	389.58	-	-	-
1981	282.77	94.71	377.55	371.48	120.92	492.43
1982	221.66	68.19	289.94	403.86	123.80	527.79
Compact						
1980	289.77	124.66	414.59	-	-	-
1981	307.25	117.51	424.82	382.06	137.51	519.38
1982	318.46	116.33	434.64	423.86	142.57	566.38
Intermediate						
1980	329.08	130.79	459.82	-	-	-
1981	350.16	182.16	531.87	359.45	193.52	552.58
1982	313.03	171.59	484.64	330.07	183.41	513.10
Full size						
1980	457.62	272.00	729.59	-	-	-
1981	581.91	188.33	764.66	581.91	195.75	771.88
1982	392.75	219.78	612.50	392.75	219.78	612.50

creases the expected repair cost for compact vehicles by over $100.

Because subcompacts and compacts together now account for the major portion of the sample mix, the increased value of E in 1982 indicates that bumpers are generally less cost effective. The limited data for intermediate and full-size cars indicate a decrease in the value of E from 1981 to 1982 for both bumper-involvement definitions. There was no difference in full-size vehicles for 1982 when the definition for bumper involvement changed. This probably is due to the small sample size involved, and the fact that full-size cars often have exposed face bars with no fascia.

STUDY RESULTS AND CONCLUSIONS

The analysis of insurance claim data has been an important technique used to assess the effectiveness of federal standards for automotive bumpers. Studies assessing each version of these standards since their inception in 1972 (1-4) have involved the use of this technique. In performing these insurance claim studies, the identification of bumper-involved claims is an essential requirement. Recent changes in automotive design have complicated the process of identifying bumper involvement. This study examined several different criteria that are currently applicable to identify bumper-involved insurance claims. The implications of each of these criteria in influencing the results of claim analyses were considered.

The primary findings of this study were as follows:

1. As a result of newer designs, the face bar damage criteria used in previous bumper claim analyses are no longer as useful as criteria that consider both face bar and fascia damage.
2. If only face bar damage is considered, claims for bumpers using newer, hard-plastic fascia are not included. In the case of soft face designs, considering just face bar damage would eliminate claims in which only the fascia was damaged.
3. A criteria that classifies a claim as bumper-involved if the face bar and/or fascia is damaged will generally cover the widest spectrum of bumper involvement.
4. Due to new soft-face designs, either the face bar or the face bar-fascia damage criteria may overstate bumper involvement relative to the bumper protection standards. The bumper standards are expressed in terms of exterior damage. In some cases where a gap exists between face bar and fascia, it is possible for an impact to damage a covered face bar, yet the outer fascia rebounds and appears undamaged. Such impacts would pass the bumper standards but constitute bumper involvement by either the face bar or face bar-fascia damage criteria used in this study. However, these criteria are considered appropriate for an analysis of the factors influencing bumper performance.
5. A cost-effectiveness measure was developed to quantify the risk or expected expense of repairing a vehicle in the first-year ownership resulting from a low-speed accident. The usefulness of this measure in interpreting insurance claim results was demonstrated in that (a) it showed that the face bar damage criteria underestimated 1982 claim involvement, (b) changes in cost-effectiveness are due primarily to changes occurring in front impacts, and (c) cost-effectiveness generally decreases with increased vehicle size.

This study strongly suggests that damage to either bumper face bar or fascia is currently the most appropriate criterion to be used in evaluating bumper performance on the basis of insurance data. Future studies of relative bumper performance should consider the effect of bumper design changes in the choice of damage criteria used.

It is also recommended that the cost-effectiveness measure E, (described in this paper), should be employed in future claim studies.

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Analysis of the Performance of 1981 and 1982 Automotive Bumpers on the Basis of Bumper Design and Manufacturer

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ABSTRACT

The effectiveness of the crash-protecting automobile bumpers required by the National Highway Traffic Safety Administration (NHTSA) for 5-mph impacts was studied through an analysis of insurance claims filed with the State Farm Insurance Company, Inc. Claims were analyzed for model year 1981 and 1982 vehicles. The performance of bumper systems was compared on the basis of bumper design and automotive manufacturer. Performance was measured on the basis of the proportion and average repair costs of insurance claims involving bumper damage. Other factors influencing bumper performance were studied including (a) criteria used to identify bumper damage claims, (b) market class, and (c) impact point.

Under a contract with the National Highway Traffic Safety Administration (NHTSA), insurance claim data were analyzed to assess the performance of automotive bumpers designed to conform to NHTSA's exterior protection standards for 5-mph impacts (1).

These standards establish requirements for bumper protection of both safety and nonsafety items in low-speed collisions. Effective with model year 1980 passenger cars, requirements were added to minimize damage to the bumper face bar itself.

Although NHTSA has issued various standards for bumper performance since 1973, this study analyzed bumper systems conforming to the version of the standards in effect for model years 1980 through 1982. Although all bumpers manufactured during this period were required to meet identical protection standards, considerable variations in bumper performance were observed among different bumper designs and automotive manufacturers. Differences were also observed on the basis of market class and impact direction.

In this paper bumper performance is compared in terms of design and manufacturer. Performance is measured on the basis of the proportion and average repair costs of insurance claims involving bumper damage.

Data for this study were obtained from the State Farm Insurance Company, Inc., and represent a nationwide sample of insurance claims from the company's claim service centers. Data for model years 1981 and 1982 were used for the design and manufacturer analyses.

An additional source of information for this study was the published results of a detailed description (2) of 1982 automotive bumpers performed for NHTSA by the Pioneer Engineering and Manufacturing Company. That study represented a "tear-down" analysis of the bumper systems of 49 different 1982 makes and models. Results of the tear-down analysis provided the basis for identification of bumper designs.

EXPERIMENTAL DESIGN

In this study, only claims involving current model year vehicles in which a bumper was either repaired or replaced were considered. Claims with damage to front bumpers from rear impacts or vice versa were not considered. Experiments were designed to stratify and compare insurance claims on the basis of bumper design and bumper manufacturer. Within these experiments, other factors were considered:

1. Impact point (front, rear);
2. Vehicle size (subcompact, compact, intermediate, full size); and
3. Criteria determining bumper involvement (damage to face bar, fascia, or both).

Vehicle size classes were defined by the accepted criteria used by the insurance industry as follows:

Vehicle Size	Wheelbase (WB) Length (in.)
Subcompact	≤ 101
Compact	$101 < WB \leq 111$
Intermediate	$111 < WB \leq 120$
Full size	> 120

These classifications were consistent with those used in previous bumper claim studies (3-5) and offered the ability to easily compare results of studies.

Two measures of effectiveness (MOEs) were employed to judge bumper performance. These included (a) the proportion of property damage claims involving a bumper and (b) the average repair costs of bumper-involved claims.

Statistical comparisons were performed by using hypothesis tests with a 95 percent confidence level for the differences between claim proportions and mean costs.

ANALYSIS OF BUMPER DESIGNS

Several questions were addressed by this analysis and are as follows:

1. Did any designs perform substantially better or worse than others?
2. How do newer soft face designs influence bumper performance?
3. Are different criteria needed to identify bumper-involved claims based on design? If so, which criteria are best suited to each design?

To gain an understanding of the relationship between bumper design and bumper claim involvement, three different criteria were examined to classify an insurance claim as involving bumper damage. These criteria included repair or replacement of (a) the bumper face bar (fascia may or may not be damaged), (b) only the bumper fascia (excludes cases in which both fascia and face bar damage occurs), and (c) the face bar, the bumper fascia, or both.

Ludtke and Kaminski (2) provided the basis for the identification of bumper designs. That study was a tear-down analysis of the bumper systems of 49 different 1982 subcompacts and compacts. The following three categories of bumper designs were identified:

- Hard face bar or fascia (H),
- Soft cover over bumper only (S/B), and
- Grille integral with bumper soft cover (S/G).

Hard (H) designs are typically found in traditional bumpers in which a metal material such as aluminum or steel serves as an exposed face bar. A newer version of this design uses plastic instead of metal. In such cases the plastic surface is often considered a hard fascia.

Soft designs generally employ a polyurethane surface (fascia) to cover a metal face bar or bumper reinforcement. These designs fall into two categories. In the more prevalent case the soft fascia covers only the bumper (S/B). In a variation of this design, vehicles such as the Chevrolet Camaro and the Pontiac J2000 integrate the soft bumper cover with the front grille (S/G).

Ludtke and Kaminski (2) identified and categorized the front and rear bumper systems of each of 49 makes and models by design. In some cases only the front bumper employed a soft design whereas in other cases only the rear bumper did.

Insurance claims were found for 38 of these 49 makes and models. These were all either subcompacts or compacts. Claims for each of these classes were compared by design. No compacts were found with the integral grille and soft cover design. Claims for front and rear impacts were analyzed separately.

Statistical comparisons examined both the proportion of bumper-involved claims and the average repair costs of these claims. For the proportion analysis, the number of front and rear bumper claims was aggregated for each market size class and design. Claim proportions relative to the total number of claims for each market class were then computed. Within each market class, the claim proportions by design and impact point were statistically compared using the hypothesis test for proportion differences.

The same statistical comparisons were performed for the analysis of average repair costs. In each case the average repair cost was computed for each market class-design-impact point combination. The differences among average costs were statistically tested using the hypothesis test for the difference between means at the 95 percent confidence level. Each set of statistical comparisons was performed three times to test each of the three criteria used to identify bumper-involved claims.

PROPORTION ANALYSES OF BUMPER DESIGNS

The results of the three sets of statistical comparisons performed on bumper claim proportions are given in Table 1. Also given are claim proportions for each involvement criteria by market class, design, and impact point.

Face Bar Damage

In soft cover designs (S/B and S/G) the face bar is shielded behind the soft bumper fascia. In studying soft designs, the face bar damage criterion would likely identify the more severe claims in which both the fascia and the face bar were damaged. Therefore it was not surprising that the proportion of face bar involvement was shown to be lower for both soft designs than for the hard design.

For compact vehicles only the hard fascia (H) and soft-cover bumper (S/B) designs could be compared. The sample size for this analysis was extremely small. In both front and rear comparisons, the S/B design had significantly lower claim proportions than the hard design. In total, claim proportions for the compacts using S/B design were 35 percent lower than those with a hard design.

Subcompact vehicles using the S/B design also had a significantly smaller proportion of claims than those with the hard design. This was shown primarily for front impacts. The S/G design was used for front bumpers only and the claim proportions for this design fell between the S/B and the hard fascia values. In comparing both soft designs (front impacts only), the integral grille and bumper cover design exhibited a significantly higher proportion of face bar damage. Therefore, considering subcompact claims for front impacts, vehicles with the S/B design had the lowest proportion of bumper-involved claims.

TABLE 1 Summary of Claim Proportion Analyses for Bumper Designs, 1982 Model Year

Involvement Criteria and Vehicle Size	Claims by Design, Size and Involvement Criteria (% of total)			Total Bumper-Related
	Design	Front	Rear	
Face bar damage				
Subcompact	H	21.4	9.7	31.0
	S/B	10.0[a]	6.4	16.3[a]
	S/G	16.2[b]	0.0	16.2[a]
Compact	H	31.0	16.5	47.5
	S/B	9.1[a]	2.9[a]	12.0[a]
Fascia only damage				
Subcompact	H	5.4	2.9	8.3
	S/B	21.9[a]	13.0[a]	34.8[a]
	S/G	36.0[a,b]	0.0	36.0[a]
Compact	H	2.5	1.6	4.2
	S/B	24.5[a]	6.8[a]	31.3[a]
Face bar and/or fascia damage				
Subcompact	H	26.8	12.6	39.3
	S/B	31.8[a]	19.3[a]	51.1[a]
	S/G	52.2[a,b]	0.0	52.2[a]
Compact	H	33.6	18.1	51.7
	S/B	33.6	9.7[a]	43.2[a]

Note: H = Hard Fascia, S/G = Grille Integral with Bumper Soft Cover, and S/B = Soft Cover over Bumper. Numbers may not sum to total due to rounding.

[a]Difference in claim proportions relative to 1982 Hard Bumper Design is significant at a 5 percent confidence level.

[b]Difference in claim proportions relative to 1982 S/B Bumper Design is significant at a 5 percent confidence level.

Fascia-Only Damage

This criterion considered claims in which the bumper fascia was damaged but the face bar was not. (This set of claims is mutually exclusive from the claims identified by the previous criterion.) Fascia damage for hard designs is applicable only to a few makes and models such as the Honda Civic and Accord, which have hard plastic fascia. Hard plastic fascia exhibit substantially lower claim proportions than either soft fascia independent of impact point and market class. Again, it is observed that the S/G design exhibited significantly higher claim proportions than the S/B design.

Face Bar and/or Fascia Damage

This criterion considered claims in which either the face bar or fascia, or both, were damaged. The sample sizes for this case were numerically equal to the sum of the sample sizes for the previous two criteria. This criterion accounts for all makes and models equipped with some type of hard face bar or fascia. In addition, this criterion accounts for all bumper-involved claims for soft designs because it includes consideration of the more extreme cases in which both the face bar and fascia are damaged as well as cases in which only the fascia is damaged.

For the first time, important differences emerged between subcompacts and compacts. Subcompacts with the S/B soft design exhibited significantly higher claim proportions than did those with the hard design regardless of impact point. subcompacts with the S/G design exhibited a further significant increase in proportions relative to those with the S/B design.

Interestingly enough, none of these findings were observed for compacts. In that case there was no difference in claim proportions for front impacts between the hard and the soft cover designs. Vehicles with the S/B design exhibited significantly lower claim proportions for rear impacts than did those with a hard fascia design. However, the sample size for this result was small.

REPAIR COST ANALYSIS OF BUMPER DESIGNS

Table 2 gives the results of the comparisons of average repair costs for the three bumper designs. The same three criteria for bumper involvement employed in the proportion analysis were also used here.

Face Bar Damage

This criterion identifies claims in which both fascia and face bar damage is likely in soft designs. Therefore, it might be expected that the average repair costs for soft designs would be higher than for those vehicles with a hard design. Although both soft designs appeared to have higher repair costs than the hard design for subcompacts, only the higher costs for the S/G design were statistically significant. According to the data in Table 2, a subcompact experiencing a front collision with face bar damage was approximately $540 more expensive to repair if it had an S/G bumper instead of a hard bumper. No significant differences were observed for compacts.

TABLE 2 Summary of Repair Cost Analyses for Bumper Designs for 1982 Model Year Vehicles

Involvement Criteria and Vehicle Size	Average Repair Costs ($) (1982 $)			Average Bumper-Related
	Design	Front	Rear	
Face bar damage				
Subcompact	H	1,300	933	1,186
	S/B	1,445	984	1,265
	S/G	1,840[a]	0	1,840[a,b]
Compact	H	1,391	922	1,228
	S/B	1,264	869	1,170
Fascia-only damage				
Subcompact	H	1,190	668	1,006
	S/B	1,332	902[a]	1,172[a]
	S/G	976[b]	0	976[b]
Compact	H	735	538	658
	S/B	1,132[a]	784	1,056[a]
Face bar and/or fascia damage				
Subcompact	H	1,278	872	1,148
	S/B	1,368	929	1,202
	S/G	1,244	0	1,244
Compact	H	1,342	888	1,183
	S/B	1,167	810	1,088

Note: H = Hard Fascia, S/G = Grille Integral with Bumper Soft Cover, and S/B = Soft Cover over Bumper.

[a]Difference in claim costs relative to 1982 Hard Bumper Design is significant at a 5 percent confidence level.

[b]Difference in claim costs relative to 1982 S/B Bumper Design is significant at a 5 percent confidence level.

Fascia Damage

This criterion identifies claims on the basis of fascia damage (excluding claims with face bar damage). It provides the opportunity to compare repair costs for fascia damage claims for hard and soft fascia designs. In this case, S/B designs exhibited significantly higher costs than hard designs for rear impacts to subcompacts and front impacts to compacts. When results for both impact points were averaged, repair costs for vehicles with S/B bumpers were significantly higher than for those with the hard design. Subcompacts with S/B bumpers were approximately $170 more expensive to repair than those with hard bumpers. Compacts with S/B bumpers were $400 more expensive to repair than those with hard fascia bumpers. In a reversal of the previous findings, repair costs for the S/G design were numerically lower than those for both other designs and significantly lower than the S/B design.

Face Bar and/or Fascia Damage

There were no statistically significant cost differences in any comparison in this case.

RESULTS OF DESIGN COMPARISONS

As a result of the comparison of claim proportions and average repair costs of designs, the following observations were noted:

1. Results for each design differed on the basis of the criteria used to identify bumper-involved claims. Each criterion offers different implications for understanding the performance of each design.
2. The face bar-fascia damage criterion appears overall to be the single, most useful means for comparing the three bumper designs. Considering only face bar damage eliminates claims for vehicles using newer hard-plastic fascia. In the case of soft fascia designs, the consideration of face bar damage only would eliminate claims in which only the fascia was damaged.
3. Using the face bar-fascia damage criterion, both of the newer soft face designs exhibit significantly higher claim proportions for subcompacts than does the traditional hard design. This is true regardless of impact point.
4. These findings did not hold for compact vehicles. In that case there was no difference in front impact claim proportions between the hard and soft cover designs. Vehicles with the S/B design exhibited significantly lower claim proportions for rear impacts than those with the hard fascia design.
5. In terms of damage to the bumper face bar, both soft face designs had lower claim proportions for front impacts than did the hard fascia design. In the case of the soft cover over the bumper (S/B), this reduction was significant.
6. Of the two soft designs, vehicles equipped

with front bumpers of the S/G design consistently experienced higher claim proportions for both fascia and face bar damage.

7. No significant differences in average repair costs were found among designs on the basis of the face bar-fascia damage criterion. The maximum repair cost difference among designs was approximately $100.

8. Claims with face bar damage appeared to be more costly for subcompacts with soft designs than for hard designs. The increase for S/G designs was significant. Bumper design differences among compacts did not have any significant effect on average bumper claim costs.

9. Claims with fascia damage without face bar damage were significantly more costly to repair for the S/B design than for the hard design. In this case the S/G design was cheaper to repair than either of the other two and significantly cheaper than the S/B design.

ANALYSIS BY BUMPER MANUFACTURER

This experiment examined the 1981 claim experience of different manufacturers to determine whether any discernible difference exist. If so, certain approaches to the manufacture of bumpers might be found to be more effective than others. Differences among manufacturers might be explained in terms of the mix of designs within each manufacturer's sample.

This experiment differed from manufacturer analyses performed in the previous insurance claim studies (3-5) by providing direct statistical comparisons of manufacturers. In previous studies, each manufacturer was considered separately. Comparisons focused on a manufacturer's claim experience between model years representing different versions of the bumper standards. The emphasis was on determining how the changing standards were influencing the claim experience of each manufacturer.

Because this study examined a period during which the standard remained unchanged, the experiment was revised to compare the claim experience of each manufacturer within a single model year. The larger 1981 sample was chosen for analysis.

Comparisons, which were similar to the analysis of bumper designs, were undertaken to determine whether the proportion of bumper-involved claims and the average repair costs of these claims differed between manufacturers. The following comparisons were included:

1. General Motors (GM) versus Ford,
2. GM versus Chrysler,
3. GM versus foreign manufacturers,
4. Ford versus Chrysler,
5. Ford versus foreign manufacturers, and
6. Chrysler versus foreign manufacturers.

Each comparison stratified claims by market class and impact point. The criterion used for bumper involvement was damage to the bumper face bar or fascia, or both.

Not every make and model produced by each manufacturer was represented in the insurance claim sample. A total of 36 makes and models were available for the GM sample, 27 for Ford, 15 for Chrysler, and 64 for the foreign manufacturers. A complete listing of all makes and models included in this experiment is available in Abramson and Yedlin (1).

PROPORTION ANALYSES OF BUMPER MANUFACTURERS

Table 3 contains a summary of the statistical comparisons of claim proportions among the four manufacturer categories. Cases with minimal sample sizes were eliminated from this table.

TABLE 3 Summary of Claim Proportion Analyses for Bumper Manufacturers for 1981 Model Year Vehicles

Vehicle Size and Manufacturer	Claims by Manufacturer and Size (% of total)		Total Bumper-Related
	Front	Rear	
Subcompact			
GM	28.9[a]	11.0	39.9
FD	23.9[b,c,d]	13.3	37.3[c,d]
CH	30.8[a]	12.6	43.5[a]
FN	28.5[a]	14.1	42.6[a]
Compact			
GM	30.5[a]	17.0[d]	47.5[a,d]
FD	21.0[b]	16.2	37.1[b]
FN	27.4	10.3[b]	37.7[b]
Intermediate			
GM	23.5	18.3	41.9
FD	18.4	19.6	38.0
Full size			
GM	22.7	18.8	41.4
All classes			
GM	28.8[a]	16.5[c,d]	45.2[a,c]
ED	22.3[b,c,d]	15.0	37.3[b,c,d]
CH	30.5[a]	12.5[b]	43.0[a]
FN	28.4[a]	14.1[b]	42.5[a,b]

Note: GM = General Motors, FD = Ford, CH = Chrysler, and FN = foreign manufacturers.

[a]Difference in claim proportions relative to Ford is significant at a 5 percent confidence level.

[b]Difference in claim proportions relative to GM is significant at a 5 percent confidence level.

[c]Difference in claim proportions relative to Chrysler is significant at a 5 percent confidence level.

[d]Difference in claim proportions relative to Foreign is signficiant at a 5 percent confidence level.

A comparison of GM with Ford (Table 3) shows that Ford subcompacts and compacts exhibited a significantly lower proportion of front bumper-involved claims. Because of the prevalence of subcompacts and compacts in the sample, these results were also reflected in the aggregate market class sample. No significant differences emerged for rear bumpers. In a comparisions of GM with Chrysler, Chrysler appeared to have a significantly lower (4 percent) proportion of rear bumper-involved claims in aggregate. However, a small sample size was available for Chrysler, which precludes assigning much weight to this finding.

An examination of GM and foreign makes revealed no significant differences for subcompacts, and the sample sizes for other classes were insufficient for analysis; however, in aggregate, the samples were sufficient and it was shown that the proportion of rear impact claims was significantly less (2 percent) for the foreign makes than for GM.

A review of GM and these other manufacturers showed that Ford subcompacts and compacts had lower claim proportions for front impacts. In aggregate, Chrysler and the foreign makes exhibited lower claim proportions for rear impacts. Compared with Chrysler, Ford subcompacts experienced significantly lower (7 percent) claim proportions for front impacts. In aggregate, Ford had significantly lower (6 percent) claim proportions for all bumper-involved claims in the two manufacturers' samples. Comparing Ford vehicles with foreign makes, it was again found that Ford subcompacts had a significantly lower (approximately 5 percent) proportion of claims for front impacts. This was also reflected in lower claim proportions for all bumper-involved claims in the sample. Sample sizes were insufficient for a comparison between Chrysler and foreign vehicles except for subcompacts and aggregate manufacturer claims. In these cases there were no discernible differences between Chrysler and the foreign makes.

REPAIR COST ANALYSES OF BUMPER MANUFACTURERS

The same six sets of comparisons were performed on the average repair costs of bumper-involved claims by manufacturer. These are given in Table 4. All 1981 costs are given in 1982 dollars and an inflation rate of 9.36 percent was used.

Comparing GM and Ford, Table 4 reveals that GM had significantly lower average repair costs for its subcompacts and compacts. This was due primarily to differences of between $300 and $400 in the costs of repairing front impacts. The small number of Ford compact vehicles in the sample, however, diminishes the weight of these findings for compacts. When all available claims for Ford and GM vehicles were examined, GM's repair costs were a significant $133 less than Ford's.

TABLE 4 Summary of Repair Cost Analyses for Bumper Manufacturers for 1981 Model Year Vehicles

Vehicle Size and Manufacturer	Average Repair Costs (1982 $ assuming a 9.36 percent inflation rate)		Average All Bumper-Related
	Front	Rear	
Subcompact			
GM	1,168[a,b]	864	1,084[b]
FD	1,451[c,d]	998	1,289[c,d]
CH	1,115[a,b]	939	1,064[a,b]
FN	1,368[c,d]	881	1,207[c]
Compact			
GM	1,224[a,b]	829	1,083[a,b]
FD	1,659[d]	868	1,312[a,d]
FN	2,111[d]	1,040	1,819[b,d]
Intermediate			
GM	1,564	1,043	1,334
FD	1,322	1,047	1,180
Full size			
GM	2,568	1,044	1,864
All classes			
GM	1,300[a,b]	884	1,148[a,b]
FD	1,495[c,d]	964	1,281[c,d]
CH	1,194[a,b]	919	1,114[a,b]
FN	1,409[c,d]	897	1,240[c,d]

Note: GM = General Motors, FD = Ford, CH = Chrysler, and FN = foreign manufacturers.

[a]Difference in claim proportions relative to Foreign is significant at a 5 percent confidence level.

[b]Difference in claim proportions relative to Ford is significant at a 5 percent confidence level.

[c]Difference in claim proportions relative to Chrysler is significant at a 5 percent confidence level.

[d]Difference in claim proportions relative to GM is significant at a 5 percent confidence level.

No important differences were noted between claims for GM and Chrysler vehicles. Sample sizes permitted inferences only for subcompacts and the aggregate vehicle category. In aggregate, the difference between these manufacturers was $34.

As it did in comparison with Ford, GM showed a pattern of significantly lower costs than its foreign counterparts. Again, this was due to lower repair costs for front impacts involving subcompacts and compacts. The small number of foreign compacts diminishes these results for compacts.

A review of Ford and Chrysler revealed that Chrysler subcompacts apparently had significantly lower repair costs for bumper-involved claims resulting from front impacts. Repair costs for Chryslers in this case were approximately $335 less than for their Ford counterparts.

A comparison of average repair costs for Fords and foreign cars revealed little of significance. Although Ford compacts displayed significantly lower repair costs, the sample sizes for this comparison were small.

In a comparison of Chryslers and foreign cars, the Chryslers exhibited significantly lower repair costs due to lower costs for front impacts involving subcompacts. Sample sizes were too small to draw inferences for other market classes.

RESULTS OF MANUFACTURER COMPARISONS

Ford 1981 subcompacts experienced a significantly lower proportion of bumper-involved claims for front impacts than did all other manufacturers studied. Because of the prevalence of subcompacts in the samples for each manufacturer, this result was also found to be true for the aggregate set of vehicles for each manufacturer.

In terms of claims for rear impacts, there were no important differences among Ford, Chrysler, and the foreign makes studied. However, when the aggregate set of vehicles by manufacturer was considered, both Chrysler and the foreign makes showed a significantly smaller proportion of bumper-involved claims than did GM for rear impacts.

The notable differences in average repair costs were in front-impact claims involving subcompacts. There appeared to be a two-tiered cost structure for the four manufacturer categories. One level of costs existed around the range of $1,115 to $1,168 for Chrysler and GM. A second higher level of costs in the range of $1,368 to $1,451 existed for foreign cars and Fords. Comparisons within each level were not significant. Any comparisons between manufacturers at different levels were significant. Therefore, GM's and Chrysler's repair costs for front-impact subcompact claims were significantly lower than either foreign manufacturers' or Ford's.

For compact vehicles, GM exhibited significantly lower repair costs than did the Ford and foreign vehicles studied. This was due primarily to the lower repair costs for front impacts and was based on a small sample.

CONCLUSIONS

During a period of time when all bumpers were required to meet NHTSA's exterior protection standards for 5-mph impacts, differences were observed in bumper performance among various bumper designs and manufacturers. These differences were found by examining insurance claim data to identify the proportion and average repair costs of bumper-involved claims by both design and manufacturer.

By employing hypothesis tests for both proportions and means at the 95 percent confidence level, the following important observations were noted for each factor:

Bumper Design

1. Subcompacts with newer soft face designs exhibited significantly higher bumper claim proportions than did those with traditional hard designs. This was observed for both front and rear impacts using the face bar-fascia damage criteria (Table 1).

2. Compacts exhibited no difference in claim proportions for front impacts between hard and soft designs. Compacts with soft face designs indicated a significantly lower (8 percent) proportion of rear-impact bumper claims. These results were determined using the face bar-fascia damage criterion for bumper involvement (Table 1).

3. Vehicles equipped with bumpers in which the

grille is integral with a soft bumper cover experienced the highest claim proportions for front impacts on the basis of the face bar-fascia damage criterion (Table 1).

4. No significant differences in average repair costs were found between designs by the face bar-fascia damage criteria. The maximum repair cost differences between designs were approximately $100 (Table 2).

Bumper Manufacturer

1. Ford 1981 subcompacts exhibited a significantly lower proportion of front-impact bumper claims than did subcompacts studied from GM, Chrysler, and foreign manufacturers. These differences ranged from approximately 5 to 7 percent (Table 3).

2. Aggregating claims by manufacturer revealed that Chrysler and foreign models had a significantly lower proportion of rear-impact bumper claims than the GM vehicles in the sample. These differences ranged from 2 to 4 percent (Table 3).

3. Notable differences in average repair costs between manufacturers appeared for front-impact claims involving subcompacts. A two-tiered cost structure emerged with Chrysler and GM at a level between $1,115 and $1,168 and foreign and Ford vehicles between $1,368 and $1,451, respectively. Chrysler's and GM's costs for these front-impact subcompact claims are significantly lower than those for either foreign manufacturers or Ford (Table 4).

Because differences were noted among bumper designs, these might explain some of the differences observed among manufacturers. This presumes that the sample for each manufacturer contained a different mix of bumper designs. However, other factors may also play a role in understanding bumper performance differences among manufacturers. Another experiment performed under this research effort examined the performance of bumpers on an individual make-model basis (1). When individual models from different manufacturers were compared, significant claim differences were still observed even when the same bumper designs and materials were used. This suggests that differences in overall car design could also explain bumper claim differences among manufacturers. The role of general automotive design in bumper claim experience is an area that requires further investigation.

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Removal of Roof-Mounted Emergency Lighting from Police Patrol Vehicles: An Evaluation

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ABSTRACT

In 1982, based on a study of fuel use and vehicle accidents, the Illinois Department of State Police began a test of the effects of removing roof-mounted emergency lights from police patrol vehicles. The test group consisted of 120 vehicles, half of which had their roof-mounted lights removed. The vehicles were randomly issued in pairs to officers who had similar patrols in rural regions. After 6 months, the fuel economy, vehicle accidents, and productivity of the officers were compared. Significant improvements were found for those officers driving vehicles without roof-mounted lights. More vehicles without roof-mounted lights were placed in service in early 1983. This study compares 208 vehicles with and without roof-mounted lights for the April 1982 through January 1984 time period. The officers drove these vehicles more than 5.5 million miles. All officers had similar driving records before the study was conducted. The results show that those officers who drove vehicles without roof-mounted lights improved their fuel mileage by 7 percent, were 25 percent more productive in speed enforcement (but not in overall enforcement), and were involved in 65 percent fewer accidents per million vehicle miles traveled. All results are statistically significant. The findings suggest that removing roof-mounted lights from police vehicles that patrol rural regions reduces fuel and accident costs and improves productivity.

In April 1982, the Illinois Department of State Police (DSP) began testing 60 marked patrol vehicles without roof-mounted emergency lights. Those vehicles were selected at random from 120 marked vehicles that were placed in service that year. Emergency lighting was placed inside the grille and on the back window ledge. The basis for this change was a study conducted by Stoica for the DSP in 1982 that recommended that the light bars be removed to save fuel (1). The study also found that drivers of unmarked police cars (without roof-mounted lights or state police markings) tended to have fewer accidents (1,p.7).

The 120 police vehicles (squads) introduced in 1982 were evenly divided into two groups: those with and those without roof-mounted emergency lights. All vehicles retained traditional state police markings including striping, decals, and the words "State Police." The test cars were randomly distributed to pairs of field officers with similar patrols in each district. In Illinois, the squad is an officer's permanent vehicle. The choice of which officers would receive vehicles was made without referring to the officers' driving records. At the end of the first 6 months, the Bureau of Planning and Analysis evaluated the results of the test (2).

Even with less than 1 million mi of driving, fuel savings were significant. Those vehicles without roof-mounted lights (hereafter termed "semimarked" to distinguish them from "unmarked" vehicles) averaged 6.4 percent better gas mileage than marked vehicles (2,p.3). Officers in all 120 vehicles had been involved in only 15 accidents, a base too small to be statistically analyzed. However, accidents involving vehicles with roof-mounted lights were occurring at a rate twice that of the semimarked vehicles, as was expected (2,p.8).

In this interim period, officer productivity was evaluated. Officers driving semimarked vehicles wrote speeding citations at twice the rate of the officers who drove traditional vehicles. There were no differences in other forms of traffic enforcement (2,p.10). In a survey of officers, those driving semimarked vehicles expressed satisfaction with the new configuration. Some officers believed that the lack of roof lights only presented problems at the scene of an accident. In terms of safety, one officer's statement sums up the attitudes of the test group: "I personally like my semimarked squad. In fact, it has made me even more safety conscious knowing there is a possibility that I may not be seen" (2,p.20).

As a result of the interim evaluation, DSP began issuing semimarked vehicles. In 1984, these vehicles were also placed in service in the Chicago metropolitan region, a six-county region. Their use will be monitored closely, because the review of accidents of unmarked vehicles had shown few differences between unmarked and marked vehicles in urban regions. For instance, there was no difference in fuel economy between marked and unmarked vehicles in urban regions. Finally, the traditional use of roof-mounted lights and the lack of strong evidence of improved safety in urban regions precluded their introduction into those regions. The current success of semimarked vehicles has led to them becoming the standard vehicle statewide.

This report compares the performance of the two types of vehicles from April 1982 through January 1984. Three comparisons are made: fuel consumption, officer productivity, and vehicle accidents. The findings of this evaluation show greater differences than those discovered in the interim report, thereby enhancing the original findings.

SOURCES OF DATA AND HYPOTHESES TESTED

Data and Tests Used

The data used for this evaluation were derived from three sources maintained by DSP: first, a vehicle cost file that contained information about monthly expenditures for fuel and maintenance, fuel used, and miles driven; second, an on-line data base known as the Traffic Information Planning System (TIPS) that showed officer activity; and finally, accident reports. The latter are not contained in a data processing file; analysis of information was therefore limited because of the difficulty of obtaining data rapidly. All data cover the January 1976 through January 1984 period.

Three statistical tests were employed. Because miles per gallon is a skewed function and because of the method of recording fuel used and miles driven, parametric analysis of variance was impractical. A Wilcoxon or Kruskal-Wallis test of analysis variance (automatically chosen by the Statistical Analysis System or SAS) was therefore employed (3). Chi-square was used for the contingency tables and a t-test was occasionally applied. This test supported the non-parametric tests. The following three null hypotheses were tested:

1. Marked vehicles have the same fuel economy as semimarked vehicles,
2. Officer productivity in each type of vehicle does not differ, and
3. There are no differences in the number of accidents between the two types of vehicles.

Description of Vehicles and Drivers

Since the first marked and semimarked vehicles were placed in service in 1982, DSP has operated 208 squads marked as Division of State Troopers in line patrol. This group excludes vehicles that were issued to officers in Districts 3, 4, and 15 (Chicago and Cook County) and those used by officers other than the rank of Trooper or for other types of patrol such as truck law enforcement. Of the 208 vehicles, 128 or 61.5 percent were semimarked. During this same period, 235 State Troopers drove the vehicles on patrol. There were more officers than vehicles because transfers, promotions, and changes in assignment resulted in some officers changing vehicles. The 208 vehicles were driven 5.7 million mi, used 484,900 gal of fuel, and were involved in 49 accidents. All 208 vehicles were white with Illinois State Police markings. These data are summarized in Table 1.

TABLE 1 Summary of Data Bases Used for Evaluation (vehicles in service since 1982)

	Vehicle Type		
	Marked	Semimarked	Total
Number of vehicles	80	128	208
Percent	38.5	61.5	
Number of officers	102	133	235
Percent	43.4	56.6	
Miles driven (000,000s)	2.94	2.73	5.67
Gallons of fuel used	260,900	224,000	484,900
Accidents	37	12	49

Drivers of the first 60 pairs of vehicles issued in 1982 were chosen randomly. Each district that was scheduled to receive a vehicle submitted pairs of names of officers on similar patrols (all officers rotate through three shifts and the only consideration was the geography of the patrol). The Bureau of Planning and Analysis selected one officer of each pair to receive the semimarked vehicle. If the officer refused the vehicle, both officers were eliminated from the test.

All of the statistical tests described in the remainder of this paper divide the officers into two categories: those driving vehicles with roof-mounted lights (marked vehicles) and those driving vehicles without roof-mounted lights (semimarked vehicles). For the three measures of fuel consumption, productivity, and accidents, a separate comparison was made between the new vehicles and the older marked vehicles driven before the test. (All marked vehicles driven prior to 1982 had roof-mounted lights.) Fewer officers comprised the base for historical comparison because some drove unmarked (plain-color) vehicles.

FUEL ECONOMY, PRODUCTIVITY, AND ACCIDENTS

Fuel Consumption

The first null hypothesis tested was that the fuel usage of those officers driving semimarked vehicles was no different from that of officers driving marked vehicles. As shown in Table 2, marked vehicles traveled slightly more miles and used more gasoline. Officers in semimarked squads averaged 12.4 mpg, which is 6.9 percent better than the 11.6 mpg obtained by officers in marked vehicles. The difference is significant at the .001 level. The total cost of operation, of which fuel was the largest component, was 14.3 cents per mile for marked vehicles and 13.0 cents per mile for semimarked vehicles. This difference of 10 percent also was significant at the .001 level. The hypothesis that fuel usage was the same for semimarked and marked vehicles was rejected.

TABLE 2 Costs, Mileage, and Fuel Economy of the Tested Vehicles (1982 vehicles)

	Vehicle Type		
	Marked	Semimarked	Total
Number of vehicles	80	128	208
Miles driven (000,000s)	2.94	2.73	5.67
Average mileage	36,720	21,310	27,240
Gasoline used (gallons)	260,900	224,000	484,900
Average mpg[a]	11.6	12.4	12.1 (avg)[b]
Average cost per mile (cents)[a]	14.3	13.0	13.5 (avg)[c]

[a]Average of (a) miles per gallon and (b) cents per mile per vehicle.
[b]Wilcoxon z equals -3.628; significance equals $p < .001$.
[c]Wilcoxon z equals +4.955; significance equals $p < .001$.

Did the officers drive differently before they received the new vehicles? Table 3 shows the average gas mileages and average total costs per mile for squads driven by these officers prior to receiving the new vehicles. Since 1976, each officer has driven more than one vehicle. Because officers originally drove both marked and unmarked cars, the data are divided accordingly. Although officers currently driving semimarked vehicles had historically obtained slightly better gas mileage and had lower operating costs, the differences between them and the other group of officers were insignificant.

Other factors, such as location of patrol or distance driven, that could have influenced the current findings had no effect. Vehicles with and without light bars were distributed evenly throughout state districts. The first 120 test vehicles were assigned randomly within those districts. Patrols in the urban regions surrounding Chicago were not included in the analysis. State Police patrols outside Cook County are primarily rural. While the total miles

TABLE 3 Fuel Consumption by Vehicles Before 1982 (1976 to 1982)

Type of Vehicle Driven Before 1982	Type of Vehicle Currently Driven: Marked	Semimarked
Marked		
Number driven	105	19
Average mpg	10.25[a]	10.51[b]
Average cost per mile (cents)	18.28[c]	17.17[d]
Unmarked		
Number driven	118	10
Average mpg	10.66[a]	11.08[b]
Average cost per mile (cents)	18.08[c]	16.73[d]

[a]Wilcoxon z equals -1.254; no significance.
[b]Wilcoxon z equals -0.425; no significance.
[c]Wilcoxon z equals 0.120; no significance.
[d]Wilcoxon z equals 0.232; no significance.

driven differed slightly, the differences were insignificant.

Vehicles in this study were limited to Fords and Dodges manufactured in 1982 and 1983. As a result of the initial findings, semimarked squads became the standard issue starting in 1984 and their use has now been extended to all regions, including the urban regions of Cook County.

Based on the differences in fuel mileage found on the test (12.4 mpg for semimarked squads versus 11.6 mpg for marked squads), semimarked vehicles require less fuel. If squads average 21,310 mi of travel per year (based on data for semimarked vehicles from Table 2), the removal of roof-mounted lights will save 118.5 gal of gasoline per vehicle. At $1.30 per gallon, this equals a savings of $154 per vehicle per year. The emergency lighting installed in the grille and on the rear deck is also less costly than any roof-mounted lighting, especially the aerodynamic type.

Officer Productivity

Officer productivity was not expected to depend on the type of vehicle driven. However, it was found that officers driving semimarked vehicles wrote more speeding citations (2,pp.9-10). Moreover, a study by the International Association of Chiefs of Police also indicated that police in unmarked vehicles were more effective at enforcing the 55-mph speed limit than those in marked vehicles (4).

Shown in Table 4 are data for traffic enforcement for the April 1982 through January 1984 time period. The only category in which officers driving semimarked vehicles were more productive was in the issuance of speeding citations. The rate of 21.9 speeding citations per 100 hr of patrol in semimarked vehicles is significantly higher than the 17.7 citations per 100 hr for officers in marked vehicles. However, these same officers issued fewer citations for other violations. Therefore, with the exception of citations for speeding, the null hypothesis of no difference in productivity held.

An examination of police activity before the introduction of new vehicles, from 1979 to 1982, also showed no statistical differences between the two groups, even for speeding citations. While all the vehicles in this study had traditional State Police markings, semimarked vehicles did not readily appear to be police vehicles, particularly to approaching motorists. Because most officers use moving radar to enforce the speed limit, speeding motorists that are approaching police vehicles might be easier to detect from semimarked squads.

TABLE 4 Average Productivity of Officers in 1982 and 1983 Police Vehicles

	Vehicle Type: Marked	Semimarked	Average
Number of officers	91	99	190 (total)
Hours of patrol	2,509	2,162	2,328
Speeding citations			
Total number	444.0	474.4	459.8
Rate per 100 hr	17.7	21.9	19.8[a]
All citations			
Total number	667.9	641.3	654.0
Rate per 100 hr	26.6	29.7	28.1[b]
Including warnings			
Total number	1,894.6	1,615.4	1,749.1
Rate per 100 hr	75.5	74.7	75.1[c]
DUI citations	15.8	14.9	15.3

[a]t-test equals -2.42; significance equals $p < .02$ (deviations are not shown, but have been used for all t-tests).
[b]t-test equals -0.41; no significance
[c]t-test equals +0.45; no significance.

Police Vehicle Accidents

According to the analysis of police vehicle accidents in 1980, officers who drove marked vehicles were involved in a rate of accidents twice that of those who drove unmarked vehicles (1,p.8) (see Table 5). For every 100 marked vehicles, 26.9 were involved in accidents. The rate for unmarked vehicles was 11.7, or one accident for every 2.3 involving marked vehicles. Each of these vehicles had been driven on patrol for approximately the same number of miles.

TABLE 5 Involvement of Police Vehicles in Accidents During 1980

Vehicle Type	Accidents: Number	Percent	Vehicles: Number	Percent	Rate of Accidents per 100 Vehicles
Marked	199	87.7	741	75.6	26.9
Unmarked	28	12.3	239	24.4	11.7[a]
Total	227		980		

[a]Chi-square equals 15.54; d.f. equals 1; $p < .001$.

The null hypothesis states that there should be no difference in the number of accidents for marked vehicles versus semimarked vehicles. A comparison similar to that of Table 5 is made in Table 6. Of the 49 accidents involving all vehicles issued since 1982 (1982 Fords and 1983 Dodges), 37 or 75.5 percent involved marked vehicles and 12 involved semimarked vehicles. On the other hand, more vehicles were semimarked. As a result, the rate of accidents for

TABLE 6 Involvement of Police Vehicles in Accidents During 1982 and 1983 (21 months)

Vehicle Type	Accidents: Number	Percent	Vehicles: Number	Percent	Rate of Accidents per 100 Vehicles
Marked	37	75.5	80	38.5	46.3
Semimarked	12	24.5	128	61.5	9.4[a]
Total	49		208		

[a]Chi-square equals 12.14; d.f. equals 1; $p < .001$.

marked vehicles was 46.3 per 100 vehicles compared to 9.4 per 100 for semimarked vehicles. These data cover the 21-month period from April 1982 through January 1984. Therefore, the yearly rate of accidents per 100 marked vehicles was 26.5, which was similar to the accident rate for marked vehicles in 1980. On the other hand, the yearly rate of 5.4 accidents per 100 semimarked vehicles is lower than that of unmarked vehicles in 1980. The difference in rates is statistically significant at the .001 level.

In 1980, the ratio of accidents between marked vehicles and semimarked vehicles was 2.3 to 1. This ratio increased to 4.7 to 1 in the 1982 to 1983 period. The null hypothesis that there would be no difference in the rate of accidents was therefore rejected.

The number of accidents per million vehicle miles is shown in Table 7. The rate of accidents per million vehicle miles was 12.6 for marked vehicles and 4.4 for semimarked vehicles. Accidents involving marked vehicles resulted in higher repair costs and more personal injuries, although the differences were not statistically significant. No attempt was made to assign a cost to the injuries, but a comparison would not have been meaningful because there were no injuries to officers involved in accidents while driving semimarked vehicles.

A detailed tabulation of accidents by type is shown in Table 8. The exclusion of accidents involving vehicles on patrol, vehicles used for miscellaneous business, and vehicles left unattended leaves a base of 13 accidents for both types of vehicles. Of these accidents, 10 or 77 percent involved marked vehicles, which is a base too small to be statistically analyzed.

One concern expressed in the previous survey of officers was that the semimarked vehicles might be more vulnerable to accidents when parked at the scene of an accident. However, only one accident involved a semimarked vehicle and none involved a semimarked vehicle stopped behind a violator. Two accidents occurred in marked vehicles while an officer was handling another accident, and three occurred in traffic stops. Therefore, most of the accidents involved a marked vehicle from which an officer was conducting police business and that had the emergency lights turned on.

Were those officers who drove marked vehicles during the time of the study also involved in more accidents before the study? As is shown in Table 9, records showed that 207 of these 235 officers were involved in 106 accidents, all in marked vehicles, from January 1976 to April 1982. Even though the rate of accidents per 100 officers in marked vehicles during this study is higher than the accident rate for the other officers, the difference is not statistically significant. An analysis of the variance of repair costs also showed no statistical difference.

As was shown previously, those officers currently driving semimarked vehicles were less likely to be involved in accidents during policing functions. The same patterns are not as evident when examining accidents prior to the study. It is shown in Table 10 that those officers currently driving semimarked vehicles also had a slightly better driving record.

TABLE 7 Other Characteristics of Police Vehicle Accidents

	Vehicle Type		
	Marked	Semimarked	Total
Accidents			
Total	37	12	49
Police service excluding patrol	10	3	13
Miles driven (000,000s)	2.94	2.73	5.67
Accidents per 1 million vehicle miles			
Total	12.6	4.4	8.7 (avg)
Police service	3.4	1.1	2.3 (avg)
Average accident costs	$1,020	$730	$950 (avg)[a]
Injury to officer			
None	31	12	43[b]
Injury	6	0	6[b]
Average number of vehicles involved	1.7	1.7	1.7 (avg)[c]

[a]No significance.
[b]Not computed.
[c]No significance.

TABLE 8 Types of Police Vehicle Accidents

	Vehicle Type	
	Marked	Semimarked
Number of vehicles	37	12
Police functions		
Accidents and violators	5	1
Emergency	3	1
Pursuit	2	1
Other functions		
Patrol	13	3
Unattended	8	1
Other	6	5

TABLE 9 Officer Involvement in Police Vehicle Accidents Before Study

Current Vehicle Type	Officers in Base	Accidents in Marked Vehicles: Number	Accidents in Marked Vehicles: Percent	Rate of Accidents per 100 Officers
Marked	102	57	53.8	55.9
Semimarked	105	49	46.2	46.7[a]
Total	207	106		

[a]Chi-square equals 1.29; d.f. equals 1; no significance.

TABLE 10 Types of Police Vehicle Accidents Before Study

	Current Vehicle Type	
	Marked	Semimarked
Number of vehicles	57	49
Police functions		
Accidents and violators	7	9
Emergency	11	4
Pursuit	10	7
Other functions		
Patrol	13	13
Unattended	7	4
Other	9	12

TABLE 11 Potential Savings if Marked Vehicles were Converted to Semimarked Vehicles (21-month period beginning April 1982)

Vehicle Type	Number of Vehicles	Miles Driven (000,000s)	Gallons Used	Operating Costs: Fuel	Accident	Total
Marked	80	2.94	236,900	$307,960	$ 5,590	$313,550
Semimarked	128	2.73	224,000	291,200	8,760	299,960
Actual cost	208	5.67	484,900	630,370	46,500	676,870
Potential cost	–	–	460,900	599,160	14,350	613,510
Potential savings	–	–	24,000	$ 31,210	$32,150	$ 63,360

[a]If converted to semimarked vehicles, based on actual costs incurred by semimarked vehicles.

However, the mileage driven relative to the number of accidents is unknown.

CONCLUSIONS

Accidents appear to be more likely to occur to officers driving marked vehicles; marked vehicles have poorer gas mileage; and there is no difference in productivity between the two test groups other than that officers who drive marked vehicles are less productive at enforcing the speed limit. The examination of fuel usage, productivity, and vehicle accidents involving these officers prior to receiving the new vehicles does not indicate a bias. Officers in each test group had similar driving records. Any differences found between the two groups in this study appear to be causally related to the use or lack of use of roof-mounted lighting equipment.

The findings in terms of operating costs and accident rates are important. Given an average reduction in fuel use of 118.5 gal for a fleet of 1,100 patrol vehicles, at a cost of $1.30 per gallon, a savings will result of approximately $169,400 per year, which is enough to purchase at least 16 new vehicles at the current market price. In addition, the cost of installing grille-mounted and rear window lights is less than $100 per vehicle. Aerodynamic lighting systems can cost more than $300 per vehicle.

The findings in terms of reduced accidents are even more critical. One of the strongest original arguments against the removal of light bars was officer safety. Roof-mounted emergency lights were supposed to help protect the officer. Yet, accidents involving semimarked vehicles resulted in substantially fewer injuries to officers driving those vehicles (as was shown in Table 7) than to officers driving marked vehicles. No cost was attached to injury in this study, because too few injuries occurred for an adequate analysis. However, any reduction in the injury rate increases the availability of manpower, reduces out-of-pocket costs, and reduces insurance costs.

Even if injuries are not considered, there is a difference in accident repair costs between the two sets of vehicles. Given the cost per accident for marked vehicles, repairs to the 12 semimarked vehicles could have cost more than $12,000. However, it actually cost $9,000 to repair these 12 vehicles, resulting in a savings of $3,000. Therefore, given the rate of accidents for semimarked vehicles, had all 80 marked vehicles been converted to semimarked vehicles, the savings in accident-related repair costs would have exceeded $32,150. A summary of total potential savings from the use of semimarked vehicles is shown in Table 11. The $63,360 savings for the 21-month period represents an average savings of $450 per vehicle per year based on the conversion of 80 marked vehicles to semimarked vehicles.

Why are semimarked vehicles safer? The officer quoted earlier in this paper implied that officers assume that roof-mounted emergency lights project unchallenged authority. However, the number of incidents in which police vehicles with roof-mounted lights apparently collided with other vehicles challenges this assumption. When the light bars are removed, an officer has to become a more cautious driver.

The use of light bars in urban regions was not discussed in this study because semimarked vehicles were placed only on rural patrol; no vehicles were sent to a metropolitan region. As was noted earlier, the review of fuel economy and accidents during 1980 did not show significant differences between marked versus unmarked vehicles in urban regions. The traditionalists' argument for roof-mounted lights apparently could not be overcome in urban regions. However, the success of semimarked vehicles has led to the issuance of semimarked vehicles in urban regions in 1984. Initial feedback from officers using these vehicles suggests that they accept them. Differences in operating costs, productivity, and accidents in urban regions will be the subject of a future report. Unfortunately, the vehicles were introduced in urban regions without establishing the same type of paired comparison used for the study of vehicles in rural regions.

The DSP now issues new semimarked vehicles as the standard State Police squad. Some officers, however, still prefer vehicles with roof-mounted lights. Because light bars are still on traded vehicles, these officers can be accommodated. However, if all vehicles in the patrol fleet (approximately 1,100) were semimarked, DSP could save more than $495,000 per year in fuel purchases and accident repair costs (based on a savings of $380 per vehicle per year). The increased availability of manpower because of the reduced number of injuries resulting from accidents is also significant, although difficult to quantify.

ACKNOWLEDGMENTS

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The Applicability of a Motorcycle Headlamp Modulator as a Device for Enhancing Daytime Conspicuity

S. E. JENKINS and M. R. WIGAN

ABSTRACT

Considerable research is needed before any positive steps are taken to further the general use of modulated high-beam headlamps as motorcycle conspicuity aids. Such research cannot proceed satisfactorily without rigorous measurements of the visual characteristics of a modulating device, which have so far been lacking. The purpose of this paper is to provide an example of such measurements and, in particular, to report on the measurements of the relevant photometric characteristics of the Q-Switch modulating device. The results of these measurements demonstrate that the device falls within the specifications recommended by the authors for an extended flashing-signal code to be used by motorcyclists and moped riders, and clearly show that measurements in field conditions will form an essential part of any future conspicuity program based on lights.

Flashing light signals are used extensively in the road environment. On vehicles they are used as turning indicators, hazard warning lights, and emergency vehicle identifiers. On the highway they are used to indicate roadside hazards, temporary construction work, railway crossings, and so forth. These diverse applications have the common purpose of alerting a road user immediately and certainly to an uncommon situation that is potentially hazardous or requires distinctive identification.

The use of flashing signals in the road environment has been reviewed by the authors (1). They proposed a coherent code of flashing signals for the traffic environment that encompasses and extends their applications to allow for the use of a modulated light device to enhance the conspicuity of motorcyclists, bicyclists, and moped riders. The problem of motorcycle conspicuity is widespread and important in many different countries (2-4), resulting in several investigations of the efficacy of headlamps, daytime running lights, and motorcyclist's clothing as aids to frontal conspicuity. The potential contribution of modulated lights is substantial. There have been some reports of promising conspicuity response effects from the use of modulated headlamps on motorcycles from Olson et al. (5).

Olson et al. compared many different types of conspicuity aids for day and night conditions, including low-beam, modulated high-beam, and reduced-intensity (10 percent) low-beam headlamps and various garments for conspicuity enhancement. They found that the modulated high-beam headlamp was the most effective daytime conspicuity aid evaluated. However, no details of the characteristics of the device were given.

Considerable research is needed before any positive steps are taken to further the general use of these devices as conspicuity aids. Such research cannot proceed satisfactorily without rigorous measurements of the visual characteristics of the modulating devices, which have so far been lacking. The purpose of this paper is to provide an example of such measurements and, in particular, to report on the measurements of the relevant photometric characteristics of the Q-Switch manufactured by Do-Tech, Inc., North Carolina, and used by Olson et al. (5). The results demonstrate that the device falls within the specifications recommended by the authors (1) for an extended flashing-signal code to be used by motorcyclists and moped riders, and clearly show that measurements in field conditions will form an essential part of any future conspicuity program based on lights.

PERCEPTION OF FLASHING LIGHTS

The authors (1) reviewed the current Australian specifications for flashing lights for vehicle and highway use and concluded that the specification of frequencies within the range of 0.8 to 2.0 Hz is somewhat arbitrary. This specification reflects the lack of knowledge of the effect such frequencies have on the visual system. The terminology used in the literature to describe the types of flashing signals is inconsistent and can lead to considerable confusion. The following definitions (also shown in Figure 1) are suggested as a classification of the various forms of flashing signals on the basis of their visual appearance and physical characteristics (these definitions are only suggested and may need to be modified in the light of empirical evidence):

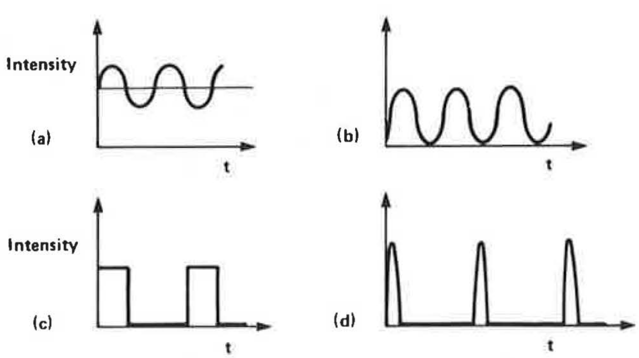


FIGURE 1 Examples of wave shapes for (a) modulating, (b) pulsating, (c) interrupted, and (d) stroboscopic signals, as defined in text.

Modulating signal--a signal that fluctuates continually and regularly between two levels of intensity (or luminance), neither one of which is zero (Figure 1a).

Pulsating signal--a signal that fluctuates from one level of intensity-to-zero. The fluctuations may or may not appear to decrease to zero depending on a number of factors (e.g., frequency and adaptation level) (Figure 1b).

Interrupted signal--a steady signal that is periodically turned off (electrically switched or physically occluded) at intervals. There are two types of interrupted signals: (a) those in which the light pulses are separated by sufficiently long, off periods for the individual pulses to be regarded as independent of one another, and (b) those in which the light pulses cannot be regarded as independent of one another. The off-period criterion is at least 300 to 400 msec. This term is normally, but not necessarily, applied to regular pulse frequencies (Fig. 1c).

Stroboscopic signal--a signal with a large ratio of intensity-to-pulse time and a pulse duration of less than 10 msec. The pulse interval is measured between intensity levels that are 1 percent of the peak intensity (see Figure 1d).

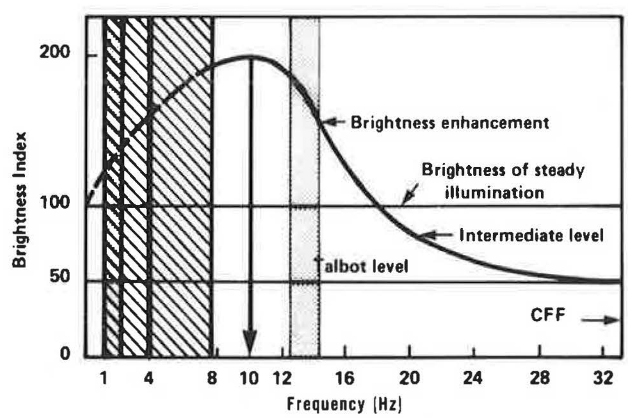
The following physical properties must be specified to uniquely describe a flashing light.

- Frequency of modulation,
- Pulse shape and intensity,
- Pulse-to-cycle fraction,
- Angular size, and
- Color.

Each of these physical properties has an effect on the visual appearance of the light and all of the properties interact with one another. The appearance of the flashing light is also affected by the level of background luminance, the presence of other lights, and the location of the flashing light in the visual field.

If flashing lights are to be used in the road environment, it must be ascertained whether they are to be seen under threshold conditions or suprathreshold conditions, because quite different effects are apparent in the two regimes. Flashing lights used to warn of roadside hazards should be visible from as great a distance as possible and therefore should be first seen in the threshold regime. Flashing lights on vehicles are generally seen at much closer distances and are often a means of enhancing the vehicle's conspicuity; they should therefore be viewed under suprathreshold conditions. It must also be decided whether the sequence of flashes is independent or interacting. The authors (1) suggest that if the period between flashes is greater than 350 msec, the flashes can be regarded as independent.

The appearance of suprathreshold flashing lights is shown in Figure 2 as a function of frequency.



The frequency regions in current use are as follows:

Frequency range of AS1742, AS1165, SAEJ590e, DR404 (2), and DR902.

Frequency of Q-Switch motorcycle headlamp (4 Hz).

Frequency range of the variable-rate Cyberlite.

FIGURE 2 Relationship between brightness of a pulsating or interrupted signal and its frequency.

The brightness enhancement effect strictly applies to the 6- to 18-Hz frequency range in which the observer is aware of a steady intensity component and a fluctuating component. (The maximum enhancement occurs at about 10 Hz.) Below approximately 4 Hz, the observer is aware of the dark phases between the light pulses (a different visual phenomenon) and the observer is no longer able to make a simple comparison with a steady light. Some proprietary conspicuity devices operate in the 3- to 4-Hz range.

Nevertheless, it is possible for the observer to make brightness comparisons between light pulses and a steady light. Such comparisons show that brightness increases as indicated by the dashed line, but this is not only the region of brightness enhancement, but also the region of conspicuity enhancement.

The different frequency ranges currently used by some devices in the Australian road environment are also shown in Figure 2. Temporally modulated lights have the following advantages over steady lights with respect to the conspicuity of a light signal:

- They enhance brightness in the 6- to 18-Hz range [Brucke-Bartley effect (6)];
- They enhance conspicuity in the 1- to 8-Hz range;
- They elicit faster response times (7,8);
- They avoid the possibility that the headlight might produce a camouflaging effect [e.g., the Yehudi camouflage lights (9)];
- They are easy to discriminate from steady lights (10);
- They materially reduce the energy requirements while maintaining conspicuity; and
- They display more urgency than passive or steady-state devices.

However, temporally modulated lights have the following limitations:

- They are not easy to discriminate from other flashing lights (10,11);
- They may cause problems for photosensitive epileptics (12); and
- They may devalue the effect of flashing signals currently in use in the road environment.

The authors, in an earlier paper (1), concluded that any proposed code for flashing signals must not contradict their established uses, but can extend them with due regard to their ergonomic principles and visual characteristics.

The characteristics of flashing signals that have proved to be the most promising are frequency and color. It was considered that an extra frequency range of 3 to 8 Hz could be included in the traffic environment that would be discriminable from other signals currently in use. The current code could also be expanded to include white.

Nevertheless, before the general use of such devices can be advocated unequivocally, much more research is required. In particular, experimental field work is needed to quantify the effects on conspicuity of the interaction between several modulated headlamps and between other flashing signals. More work is also needed to understand the perception of modulated lights in the central and peripheral fields of vision and to assess the use of other physical characteristics of modulated lights besides color and frequency as coding dimensions.

APPLICATION TO MOTORCYCLISTS

Evidence from accident statistics shows that motorcyclists are over-represented in certain types of accidents (13). In an analysis of accidents involving motorcycles in Victoria, Australia, from 1961 to 1962, Foldvary found significant differences between the ratio of motorists to motorcyclists in different types of accidents (14). In accidents involving an error of right-of-way, turning, or signaling, the motorist was more often in error. Foldvary concluded that the lack of conspicuity of the motorcycle and rider was the major contributing factor to these types of accidents. Other more recent studies have also reinforced the problems that motorcycles have with poor frontal visibility during the daytime (15-18). A flashing light would be expected to enhance the daytime conspicuity of motorcyclists for the reasons outlined earlier. The expansion of the flashing-signal code suggested by the authors might then accommodate the use of modulation devices to enhance motorcycle conspicuity without any detrimental effect on the current use of flashing signals by highway authorities. Another advantage of using a unique code for motorcycles is that it will readily identify them as a specific class of vehicle.

PHOTOMETRY OF THE Q-SWITCH HEADLAMP MODULATOR: RESULTS AND DISCUSSION

The Do-Tech Q-Switch is one of several commercially available headlamp modulators. It creates a modulation that lies within the frequency range of 3 to 8 Hz. A Q-Switch was used to provide a concrete example of the photometric properties of a headlamp fitted with such a modulator. Olson et al. (5) used the device to obtain positive conspicuity results for certain motorcycle configurations in highway conditions; however, no details of the photometric characteristics of the device were provided.

The headlamp employed for the Australian Road Research Board tests was a sealed-beam Stanley 6.1097 (12 V, 40 W/3.4 W) fitted to a 1979 Honda 1048-ml CBX. This is a large machine which, because of its ample power generation capabilities, does not require the reductions in current effected by the use of a modulated headlamp to sustain daylight use of the headlamp. The photometric measurements were made in a dark tunnel and the results are given in the following sections.

Lamp Voltage Versus Engine Speed

The photometric properties of the modulated headlamp were best measured while it was off the motorcycle because the positioning and mounting accuracy of the headlamp is greatly reduced when it is actually on a motorcycle. Nevertheless, it is obviously important to gauge the performance of the headlamp on a motorcycle. Therefore, the lamp voltage at the lamp terminals was then measured with the headlamp mounted on the motorcycle as the engine speed was held at a number of values ranging from idling to 5,500 rpm or 92 Hz (5,500 rpm corresponds to approximately 120 km/hr in top gear on this machine). Subsequent photometric measurements carried out at a known lamp voltage from a stabilized power supply could then be related back to engine speed. The results of lamp voltage as a function of engine speed are given in Figure 3.

Headlamp Intensity at Different Lamp Voltages

The headlamp was mounted in a goniometer and positioned so that the photometer recorded the maximum intensity on high beam. The power supply was stabilized and the lamp voltage was monitored at the lamp terminals. The intensity of the headlamp was found for a range of voltages from 10 to 14 V for both high- and low-beam conditions. The results are shown in Figure 4.

Measurement of Modulated Headlamp Intensity

On Motorcycle

The modulated headlamp intensity was measured while the headlamp was attached to the motorcycle because the very approximate positioning of the headlamp in

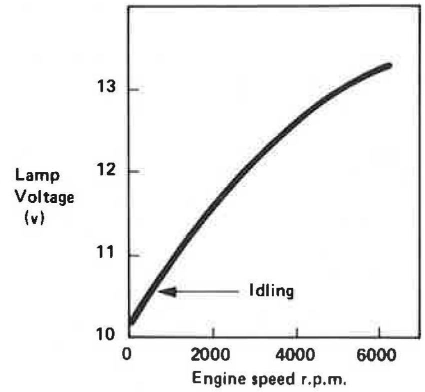


FIGURE 3 Lamp voltage (measured at lamp terminals) as a function of engine speed (measured by tachometer).

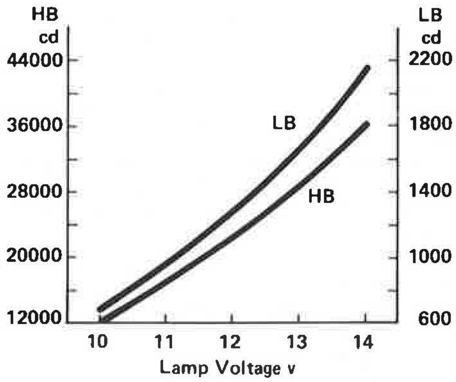


FIGURE 4 Headlamp beam intensity at the straight-on position as a function of lamp voltage for high-beam (HB) and low-beam (LB) conditions.

the yoke and the uncontrollable variations in lamp voltage are common characteristics of such vehicles on the road. The output of the photometer was displayed on an oscilloscope. Measurements were taken while the motorcycle was idling and with the engine switched off and the headlamp driven by the battery only. The maximum and minimum intensities of the headlamp are given in the following table.

	Engine Idling (cd)	Battery Only (cd)
Maximum intensity	13 400	10 460
Minimum intensity	3620	3160

Off Motorcycle

When the headlamp was mounted in the goniometer and positioned to give maximum illumination at the photometer on high-beam, the lamp voltage was set at 12.15 V. The output of the photometer was displayed on a storage oscilloscope with a wide frequency response and a calibrated time scale. The waveform of the headlamp intensity, as shown in Figure 5, is practically triangular with a frequency of 4.20 Hz. The steady-state intensity level is 21 700 cd; the maximum value of the intensity waveform is 13 920 cd (64 percent of the steady-state value); and the minimum value is 4505 cd (21 percent of the steady-state value).

The input waveform at the lamp terminals was also monitored, as shown in Figure 6. It can be seen that

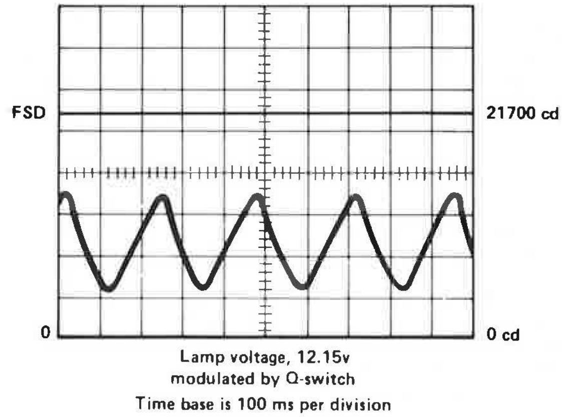


FIGURE 5 Oscilloscope trace recording of modulated headlamp intensity with headlamp mounted on a goniometer for a time base of 100 msec per division.

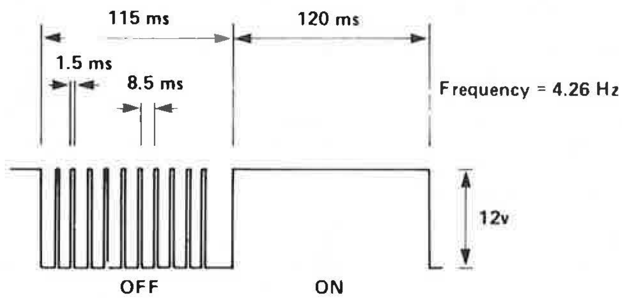


FIGURE 6 Output waveform of the headlamp modulator device.

during the off period of the duty cycle, the lamp filament received short duration pulses that would promote a slower drop of filament temperature than would otherwise occur. This would also have the effect of extending the life of the bulb. The measured frequency of the input waveform was 4.26 Hz.

The current drain of the modulation device was about 200 mA, which is negligible in comparison with the 4 to 6 A drawn by the headlamp bulb. The long-term reliability of the device has been tested independently by the Electrical Testing Laboratories, New York, who certified no degradation in performance after 2 million pulses (i.e., 6 to 7 years of average use in the United States).

It is instructive to look at another, quite different motorcycle and headlight combination. This motorcycle [a Yamaha RZ350(K), which is a type of RZ250, a popular model in the key novice rider category] had a much smaller engine capacity and the headlamp had a much higher rating (12 V, 60 W/5.5 W).

Under laboratory conditions and with a stabilized power supply, the steady-state intensity at 12.15 V was 31 600 cd on high beam compared with 21 700 cd for the first headlamp test. Of course, the frequency of the modulated headlamp intensity and the ratios of the maximum and minimum modulated intensities to the steady-state intensity are determined almost completely by the Q-Switch and thus remain the same as in the first test (64 percent and 21 percent, respectively). It was not possible to measure the steady-state high-beam intensity for the battery-only condition because the current drain was so great that the light output rapidly decreased. Consequently, the low-beam intensity would probably have better results in this combination.

Another feature of the small motorcycle and highrated headlamp combination was that the lamp voltage varied rapidly over a narrow range of engine speed from idling to 2500 rpm (42 Hz), which resulted in considerable variation of light intensity at these low engine speeds. It was also apparent that at low rpm levels, which are typical of a stationary machine awaiting a turn, the dipped beam was delivering a higher intensity than the main beam.

It should be noted that both machines were in as-new condition. The two examples of motorcycle and headlamp combinations serve to forcefully illustrate the need to combine rigorous photometric data with the results from experiments of behavioral responses. Field results differ substantially from laboratory measurements. The point of application of all such conspicuity enhancement measures is field performance on real machines.

SUMMARY

Positive on-road conspicuity effects have been reported by Olson et al. (5) using a proprietary device: the Q-Switch headlamp modulator. Considerable research is needed before any positive steps are taken to further the general use of such modulation devices as conspicuity aids. In particular, experimental field work is needed to quantify the effect on conspicuity of the interaction between several modulated headlamps and between a modulated headlamp and other flashing signals in the road environment. A greater understanding of the peripheral and foveal perception of modulated lights at suprathreshold intensities is also needed. Such research cannot proceed satisfactorily without rigorous measurements of the visual characteristics of such modulating devices, which have so far been lacking. An example of such measurements was provided in this paper by examining the Q-Switch device photometrically.

The maximum and minimum values of the intensity waveform were 64 percent and 21 percent of the steady-state value, respectively. The frequency of the modulation was 4.20 Hz and the waveform was close to triangular. This device lies within the range of specifications suggested by the authors (1) for the enhancement of the daytime conspicuity of motorcyclists. These results complement the on-road conspicuity results of Olson et al. (5) and provide a reference for permissive or regulatory considerations.

The results clearly show that measurements in field conditions, with a typical distribution of motorcycles of different ages, will form an essential part of any future lighting-based conspicuity program.

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Multi-Dimensional Assessment and Variably Intense Interventions: A Systems Approach to DUI

VINCENT D. PISANI

ABSTRACT

This paper provides a review of the literature on the seriousness of the problem of driving under the influence (DUI), legal developments, the success of DUI programs, the diversity of alcohol abusers, and the range of approaches to intervention with DUI offenders. The Alcohol and Drug Education Services Program of Cook County, Illinois, which emphasizes assessment and matching the level of intervention to client needs, is discussed.

Driving under the influence (DUI) of alcohol or other mind or mood altering substances is not in itself an illness. More properly, it is deviant behavior, a specific type of improper vehicular management. Persons who exhibit this behavior come from a variety of genetic and psychosocial backgrounds.

At best, driving is a risky business. When a variety of physical or emotional stress factors, including alcohol or drug use and abuse, come into play, the operator of a vehicle may experience an "additive stress effect" that often significantly impairs his ability to maintain control of the vehicle.

Recent interest in DUI behavior results from a variety of social, economic, and political pressures. DUI is unacceptable behavior. Dealing with it effectively requires that it be defined and measured. This behavior should be "typed," its intensity measured, and then its duration determined. Next the appropriate existing methods and levels of intervention must be matched with the configuration of these parameters as they exist in a particular person's genetic and psychosocial background. Such an approach is admittedly difficult, but it is a challenge to the behavioral scientist.

Intoxicated drivers are a diverse population and reach intervention programs by a variety of paths. The DUI offender falls into a subgroup that receives intervention as a result of legal referral. Despite the diversity, it is possible to make a few generalizations that apply to most DUI offenders. The most important is that the majority are not alcoholics or drug addicts. There is a need for programs specifically designed to handle diversity. One such program is the Alcohol and Drug Education Services Program of Cook County, Illinois. The program was founded by Reverend Ignatius McDermott in recognition of the individuality and diverse needs of DUI offenders. The program is based on more than 13 years of experience in meeting the needs of offenders through varied measures. In particular, it seeks to determine each person's unique status and to adjust measures of intervention accordingly.

This paper will begin with a brief review of the literature on the seriousness of the DUI problem, legal developments, the success of DUI programs, the diversity of alcohol abusers, and the range of approaches to intervention with DUI offenders and alcohol abusers in general. Then the approach of the Cook County program, with special emphasis on assessment and levels of intervention, the critical components of the intervention program, will be outlined.

SERIOUSNESS OF THE DUI PROBLEM

Automobile accidents are a major cause of injuries and property damage in the United States and other countries. Donovan et al. (1) report that one-third of all injuries and one-half of all fatalities are related to alcohol use. According to Donovan et al., DUI was responsible for roughly 20,000 deaths and 400,000 disabling injuries in the United States in 1976. These authors note impairment of cognitive, sensory-perceptual, and motor skills as a result of alcohol use.

Kastrup et al. (2), on the basis of data from two Danish central statistical registers, indicate that one-third to one-half of all fatalities result from traffic accidents. Higher blood alcohol levels are associated with more serious injuries. These authors estimate that 67 percent of all accidents result from the effects of alcohol consumption.

Previous studies of the impact of alcohol consumption on traffic safety support similar conclusions. DUI is clearly a major social problem, one that causes a high number of deaths, injuries, and incidents of property damage.

LEGAL ASPECTS

Guydish (3) distinguishes four responses of society to alcohol abuse and other forms of substance abuse: the legal, based on moral principles and legislation; the medical, based on a disease model and using drugs and detoxification procedures as therapy; the traditional, based on support and the achievement of abstinence; and an emerging model based on modification of individuals' contingency sets. In this century, it has been increasingly recognized that alcohol abuse is not under the full volitional control of the abuser and should be classified as "sick" rather than "bad." Given this recognition, criminal penalties of the traditional sort become less justifiable. Hall (4) notes the following weaknesses of the punitive approach: failure to change the attitudes and behavior of DUI offenders; lack of police support; unequal justice and corruption of police officers; self-defeating effects; and placing the defense counsel in the role of trying to prevent a guilty verdict, thus interfering both with aid to the individual and with protection of society from further DUI behavior.

Hart (5) points out two related developments in the United States. The first is the Uniform Alcoholism and Intoxication Treatment Act, drafted in 1971, that decriminalizes alcohol intoxication and alcoholism and provides for protective custody and voluntary treatment of persons intoxicated to the point of incapacitation. The aims of this act have not been wholly achieved, however. The second is the National Alcohol Countermeasures Program of the U.S. Department of Transportation. Under the guidelines of this program, 35 alcohol safety action projects (ASAPs) were started. These programs involved charging intoxicated drivers with an appropriate offense and sentencing these drivers to accept treatment and education as an alternative to license revocation.

Pressure for increased penalties need not interfere with programs of therapeutic intervention. However, combining legal penalties with therapeutic programs has certain problems. Kern et al. (6) note that involvement of the legal system makes participation in therapeutic intervention a result of coercion. This coercion clashes to a degree with the goal of having clients willingly commit themselves to participation in therapy. At the same time, it increases the likelihood that offenders will accept intervention. Thus, despite certain tensions, the relation between the legal and therapeutic systems is basically one of symbiosis.

SUCCESS OF DUI PROGRAMS

One general study completed by the Comptroller General of the United States (7) and a second overview by Saunders (8) revealed mixed results. However, examination of the 25 ASAP pilot projects reveals apparent advantages as well as disadvantages. Early identification of the problem and various other factors encourage acceptance of treatment. These factors include trauma of punishment, legal limits, and awareness. Swenson et al. (9), Hagen et al. (10), and Michelson (11) reporting on studies done in Arizona, California, and Florida, respectively, found little evidence of the effectiveness of short-term treatment. They found that participation in DUI programs had no significant favorable effect. In many cases, participants had worse traffic violation and accident records than did controls.

Holden (12) describes a study in which 4,126 DUI offenders were exposed to probation supervision, education and therapy, both, or neither. No combination of treatment conditions had any effect on rearrest rates after 2 years.

McGuire (13) and Salzberg and Klingberg (14) compare DUI offenders referred to programs and drinking drivers not referred to such programs. McGuire finds favorable effects on light drinkers but not on heavy drinkers. There were higher rates of alcohol-related traffic violations in the treatment group than in the control group.

Thus the evidence of the value of many existing programs is no more than doubtful. The question remains open, however, whether this is due to inherent intractability of DUI cases or to specific flaws in the programs reviewed. The Cook County program has a number of special features that are intended to avoid the problems of other programs. It is centered on division of DUI offenders into subgroups for which different treatment interventions are appropriate. Suiting the intervention to the offender may offer a path to higher success rates.

DIVERSITY OF ALCOHOL ABUSERS

Alcohol and drug abusers range from persons who have simply drunk or drugged to excess on one occasion to those who are chronically intoxicated, and from mild loss of control to severe intoxication. For the therapist, it is desirable to intervene in the milder forms of abuse because they offer an opportunity to deal with less firmly established patterns of abusive behavior. This makes DUI programs a good way of intervening early in the development of alcohol and drug abuse. It is crucial to be aware of how DUI clients differ from alcoholics or drug addicts. Intervention suited to one group may not be appropriate or effective for the other.

Pisani (15-18) suggests that alcohol and drug abusers can be optimally helped only after evaluation of the bio-psycho-social deficit present and the amount of regression caused by the abused substance. He proposes using a holistic approach that consists of five levels of intervention: assessment, education, guidance, counseling, and therapy. After such evaluation, each level is suited to specific degrees of pathology.

In additional studies, Peer et al. (19), Smart et al. (20), McCreery (21), and Hodgson et al. (22) recognize diverse subgroups of alcohol abusers. Subjects are divided into abstainers, social drinkers, semidependent drinkers, and problem drinkers. Each group calls for different treatment. Brown (23) finds clearly different patterns of drinking behavior in problem drinkers, and Saunders and Richard (24) find no such behavioral differences.

Several authors, including Panepinto et al. (25), Selzer et al. (26), Cloud (27), and Ringoet (28), point out explicitly that drunk drivers do not fit the alcoholic model and recommend treatment based on this recognition. Thus differences can be found at the psychological, the behavioral, and even the metabolic level.

Attention has also been given to identifying subtypes of DUI offenders. Scoles and Fine (29) note the diversity of such offenders as a major obstacle to successful intervention. Several studies, such as those by Kern et al. (6), Meck and Baither (30), and Wells-Parker et al. (31) link these differences to membership of varied populations as defined by such factors as age and ethnicity. Contrasting drinking drivers who complete an alcohol education program with those who drop out, they noted that noncompletion of the program is associated with nonwhite ethnicity, younger age, and higher blood alcohol content at the time of arrest. All of these findings suggest a need for recognition of age and social differences, and more specifically perhaps also of class and sex differences, in the circumstances under which DUI occurs and the proper forms of intervention.

These studies offer a diversity of pictures of alcohol and drug abusers, but they appear to favor several conclusions. First, alcohol and drug abuse takes various forms. Second, the specific form known as alcoholism or drug addiction is not necessarily a valid model for the needs and problems of DUI program clients. Third, these clients themselves are diverse, and any attempt to reduce them to uniformity is likely to lead to invalid therapeutic intervention. Skinner and Allen (32) offer one tool for such an approach to intervention: a scale designed to measure the degree of alcohol dependence in a given client. This scale, tested on 225 subjects, reveals high internal consistency. A high score is associated with more drinking, social consequences from drinking, psychopathology, physical symptoms, and failure to keep appointments for therapy. This type of approach is needed to implement the recognition of client diversity.

APPROACHES TO DUI INTERVENTION

The single most important feature of an effective program for DUI offenders is the inclusion of a variety of options and the appropriate matching of offenders and options. This may be voluntaristic, [Ewing (33)] or compulsory [Steer et al. (34)]. Both approaches seek to suit the treatment to the client; they differ primarily in their assessment of clients' ability to judge their own needs.

Intervention can take a variety of forms. The simplest is the provision of information. However, with some clients it becomes necessary to provide various forms of counseling, motivation, and therapy. Several approaches to change are suggested. Whelan and Prince (35) and Oei and Jackson (36) propose a cognitive approach designed to reinforce realistic beliefs about drinking behavior. A second approach is based on changing the client's social skills and attitudes. Orosz (37) and Holser (38) theorize that excessive drinking reflects inadequate social skills. A more traditional psychotherapeutic approach is outlined by Panepinto et al. (39), who propose that treatment begin with evaluation. Other programs have sought to train clients in behavior skills, on the assumption that the DUI offender does not wish to become incapacitated but cannot judge his drinking accurately. A final approach is direct medical therapy. Poulos (40) and Steer et al. (34) suggest that these methods are suited to clients who are physically addicted to alcohol or who have suffered long-term physical deterioration as a result of chronic alcohol abuse.

The spectrum of possible intervention runs from an educational model to a medical one. Obviously not all of these can be appropriately used with any one client, but the wide spectrum of possibilities is needed. It is necessary to provide individualized evaluation and intervention, such as "clinical" intervention, for offenders. This principle is gaining recognition, and the National Highway Traffic Safety Administration offers a manual for presentencing investigating officers that stresses the variety of types of DUI offenders and provides criteria for distinguishing among social drinkers, problem drinkers, and alcoholics.

ADES PROGRAM

The Alcohol and Drug Education Services (ADES) program of Cook County, Illinois, is an attempt to deal with the problem of DUI and related problems through varied forms of intervention designed to meet the individual offender's needs. The approach followed includes education and guidance, monitoring, punishment, and referral for counseling or therapy within a holistic modified punitive framework. Measures suited to the individual offender are selected through a systematic assessment procedure at the start of intervention.

The program was developed in collaboration with the chief judge, the Honorable Harry Commerford, and in cooperation with the court system and is presented as an alternative to the attempt to avoid conviction. The client is asked to take part voluntarily in exchange for avoiding the additional legal punishments and the status of a convicted DUI offender. Sentencing judges retain the option of imposing fines and jail sentences and suspending driving privileges. ADES gives judges the opportunity to offer a wider spectrum of response to the offense.

McDermott and Moran (41) have stated that, although the primary purpose of ADES is evaluative and educational, an equally important function is to refer clients with life problems involving alcohol or drug abuse to appropriate agencies. Motivation comes from the realization that the program is working in the client's interests. Participation is begun immediately after a court appearance during which social disapproval is expressed, and successful completion of the ADES program is generally required before probationary status is removed and driving privileges are returned. The basic purpose is to change the client's behavior by changing his attitudes and motives. External penalties are not sufficient; what is needed is a change in the client's own attitude toward DUI behavior.

The first and most crucial step in the program is assessment. ADES uses several tests and measurements to achieve this. They include a personal data form, an attitudinal study, the Michigan Alcohol Screening Test, the ADES substance abuse assessment, and an interview with an education and referral officer (ERO) during which the client completes a behavior assessment scale (BAS). The results of these measurements are used to determine a "risk factor" ranging from 0 to 3. Two subscores are computed, one for the BAS and one for all other measures. These computations are done separately by two separate individuals, a psychologist for BAS and an ERO for the other measures. They are then averaged, with greater weight given to the score obtained by the ERO. The risk factors are interpreted, and recommendations are made to the referring court. Experience with this system shows that about 20 percent of clients have a risk factor of 0, 42 percent have a risk factor of 1, 35 percent have a risk factor of 2, and 3 percent have a risk factor of 3.

After determination of a client's risk factor, appropriate interventions are selected. A basic scheme is used. In this scheme there are four broad levels of intervention after the initial assessment phase: education, guidance, counseling, and therapy. The first two are provided by ADES itself, the latter two by outside agencies in collaboration with ADES. Education and guidance are offered to all clients. The intent is to provide information that will be personally relevant and the motivation for change. Those with patterns of chronic substance abuse or other life problems are referred to outside agencies for counseling. A minority are found to have problems so severe as to necessitate medical treatment in hospital-based facilities. This level often fits the classic pattern of alcoholism or addiction to other substances.

For the latter two groups, ADES retains the role of overall coordinator and is responsible to the courts for monitoring the client's progress. Extensive records are kept. However, under Illinois law, these records are confidential and written consent of clients is required to transfer records from any subagency to ADES or from ADES to the courts. Failure to complete a program results in immediate notification of the courts and other concerned agencies. The result can be a full hearing and appropriate penalties.

Within this overall system two distinct levels of intervention have been defined. Level 1 is intended primarily for clients who lack information about the effects of alcohol on behavior and do not appear to have significant life problems. Level 2 is for clients who exhibit more profound behavioral problems.

In both levels clients undergo initial needs assessment. Level 1 clients attend four 2-hr sessions devoted to lectures, films, and discussion groups, which provide information on the effects of alcohol, the factors that trigger its use, the methods of gaining improved control over alcohol use, and the laws regulating alcohol consumption. Level 2 clients attend 12 sessions of special education and also take part in group monitoring sessions. In addition, they are referred to outside agencies. Progress of clients in both levels is assessed and reported to the court.

Within Levels 1 and 2, several distinct tracks are available: the general population program, a youthful offender program, a women's program, and a poly-drug program designed for clients aged 17 to 30 who have abused substances other than or in addition to alcohol.

These programs thus cover a wide range of client situations and offer options for mild or severe problems. This diversity is central to the design of ADES.

A comprehensive judgment on the effectiveness of ADES remains difficult to obtain. Recidivism is low. In 1980, 96.3 percent of participants had never previously taken part in ADES. A comprehensive research study was initiated to investigate the long-term effectiveness of the program. ADES makes a number of referrals of problem drinkers, concentrating the resources of other agencies on the recipients with the greatest need for them. Clinical experience reveals improvements in clients of ADES. Further, the legal system of Cook County has come to regard ADES as a useful alternative to conventional means of dealing with DUI offenders. The ADES program is unique in its use of a holistic modified punitive approach with multiple levels of intervention.

It has long been recognized that the better a program matches the actual characteristics of the target population, the more success it will attain. A wrongly conceived program will have no effect and can even be counterproductive. A too narrowly conceived program will aid one subgroup of clients but fail with other subgroups. It may be speculated that such approaches account for the majority of unsatisfactory results reported by other programs.

The Cook County ADES program rejects a stilted unidimensional response to a multidimensional human problem and instead offers a multidimensional systems approach to DUI with emphasis on assessment and levels of intervention.

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Pedestrian Flow Characteristics on Stairways During Disaster Evacuation

C. J. KHISTY

ABSTRACT

Although the design and operation of pedestrian facilities in disaster situations are much more critical than they are under everyday, normal conditions, comparatively little research has been done on people movement during disasters. A preliminary investigation of the nature of pedestrian movement on stairways in high-rise residential buildings under emergency or disaster conditions is described. Such people movement down stairways is the most crucial activity in cases of fire. It was found that current codes and regulations in regard to personal space, speed, and flow of people using stairways under emergency or disaster conditions are in need of revision. Recommendations based on the results of this study are made for designing safe stairways and for developing building code requirements. The findings can also be applied in designing stairways in stadiums, theaters, arenas, and other public facilities where stairways are a part of the pedestrian circulation system.

The movement of people down stairways of high-rise buildings is by far the most crucial activity is cases of fire. Comparatively little research has been done on people movement on stairways during emergency or disaster conditions although such movement under everyday, normal conditions has been extensively researched and documented during the last two decades (1-3). Ironically, many of the results of studies in nondisaster or nonevacuation contexts have been applied in developing building code requirements for means of egress in disaster situations (4). Because the design and operation of facilities for pedestrians under disaster conditions are generally much more critical than they are under nondisaster conditions, there is a need to investigate human behavior and movement characteristics under the former situation.

The purpose of this research is two-fold: first, to investigate human behavior under disaster conditions, such as the human response to fire, and second, to investigate pedestrian movement with respect to flow, speeds, and densities on one of the most critical links of pedestrian circulation, stairways of buildings, under disaster conditions.

Current research on pedestrian flows on stairways in high-rise residential buildings during evacuation under simulated emergency conditions is described. The results of this investigation are compared with similar findings from current literature. Recommendations based on the results of this study are made for design and operational considerations. The findings may also be helpful in designing stairways for pedestrian facilities in nonemergency contexts.

BACKGROUND

Some long-standing myths about how people behave in emergency conditions caused by natural disasters are being increasingly challenged. Recent research indicates that human behavior can be rational in emergencies and that panic rarely occurs during disasters (5). Although this may sound optimistic, there are reports that point out that immediate, rapid, well-organized evacuation of tall buildings and public places under emergency conditions appears to be the exception rather than the rule (6). Also, recent research indicates that there is a tendency to oversimplify design assumptions and the dynamics of pedestrian flow in emergency planning (4). Pauls (4) reports that even in simple evacuation drills the evacuation times observed were about twice as long as had been originally predicted.

Obviously, the current state of knowledge concerning human behavior and performance during disasters needs to be expanded. The development of building codes, standards, and criteria for designing stairs should take into consideration not only those attributes of human performance under everyday, normal conditions, but also attributes under emergency conditions. The pioneer work of Wood (7) and Pauls (4) has encouraged researchers to assess human behavior in fire emergencies and has helped to dispel inaccurate ideas of how people behave under such conditions.

STUDY DESCRIPTION AND MEASUREMENT TECHNIQUES

The main objective of this study was to investigate pedestrian flow characteristics on stairways of high-rise buildings in response to fire. Although there were no opportunities to observe these characteristics during an actual fire, the investigation was done under simulated emergency evacuation conditions with the assumption that the behavior of evacuees would be similar in real fire emergencies. During 1983-1984, a total of 21 test evacuations were observed in dormitory buildings ranging between 3 and 12 stories in height on the campus of Washington State University (WSU), Pullman, Washington. WSU's Fire Safety Department usually conducts two fire emergency drills per year for each dormitory. Drills were conducted without warning and under simulated fire conditions.

Pedestrian flow can be described in terms of speed and density (concentration):

$$q = kv$$

where

- q = pedestrian flow volume in pedestrians per foot-width of stairway per minute,
- v = pedestrian space mean speed in feet per minute, and
- k = pedestrians per square foot of stairway (density or concentration).

Time-lapse photography, at 18 frames per second, was used to film the movement of people on the stairways. A camera speed of 2 frames per second would have been adequate, but the equipment available necessitated using 18 frames per second. Filming was done on 15-m super-8 rolls. The analysis of the film was done using a hand-operated editing machine. All timing measurements were initially made in frames and subsequently converted to real time. Pedestrian speeds were obtained from the films by recording the time taken by subject pedestrians to cross two or more specified points on the stairways. Similarly, the corresponding pedestrian densities were obtained by counting the number of pedestrians within a specified area. When the individual speeds (v ft/min) and corresponding densities (k peds/ft^2) for subject pedestrians had been calculated, the corresponding flows (q peds/ft/min) were obtained from the relationship $q = kv$.

Between 3 and 15 observers were engaged in recording information and gathering data on evacuation movements depending on the size and height of the building. Portable tape recorders, stop watches, and still cameras were used to record observations. Observers generally moved along with evacuees from floor to floor and were able to collect data unobtrusively.

After the fire drills were over, a random interview of approximately 10 percent of the evacuees revealed that about 80 percent of those interviewed believed that the building evacuation was indeed in response to a genuine fire. About 99 percent of the dormitory occupants were students between the ages of 18 and 30. The stairways in the 21 dormitory buildings observed have the following general characteristics:

1. Almost all the stairways have scissors configurations (19 out of 21).
2. The risers are between 6 1/2 and 7 1/2 in. high.
3. The treads are between 11 and 12 in. wide.
4. The width of stairways varied between 4 and 7 ft.
5. All stairways have handrails.
6. The evacuation exercises were done at all hours of the day and as late as 11 p.m. Fifty percent of the exercises were during the spring and fall and 50 percent during the winter.

EVACUATION OBSERVATIONS AND RESULTS

The movement of people down passages, ramps, and stairways of buildings is by far the main physical activity in case of fire. The collection of data for such variables as spacing, density, speed, flow, queuing, and evacuation time was considered the most crucial part of this study. Observations were confined to stairways only.

This study was essentially done in two phases. Phase 1 consisted of collecting data under normal circumstances, which included peak and off-peak flows, when there was no threat of fire, and Phase 2 consisted of collecting similar data under fire emergency circumstances. It must be noted that under normal circumstances people were using the stairs as well as the elevators wherever the latter were available. Under fire emergency conditions, of course, the elevators were not operational, and hence everybody was forced to use the stairways. A total of 200 valid samples were recorded in each phase. Details regarding personal space, speeds, and flows of evacuees follow.

Personal Space

Table 1 gives the frequency distribution of horizontal stairway area occupied per person under emergency (fire) conditions and also under normal, everyday conditions. Figure 1 shows these data graphically. Under fire emergency conditions the mode and median of person occupancy were 5.5 and 7.7 ft^2 per person, respectively. In comparison, the mode and median of person occupancy under normal conditions were 6.5 and 7.8 ft^2 per person, respectively. Note that there was an increase of about 80 percent in the number of persons occupying a space of 5 ft^2 or less in case of an emergency compared with the normal situation.

TABLE 1 Frequency Distribution of Person Occupancy on Stairways

Pedestrian Occupancy (ft^2/person)	Frequency Under Emergency Conditions	Frequency Under Normal Conditions
3.5	5	1
4.5	22	6
5.5	23	20
6.5	36	42
7.5	33	40
8.5	20	22
9.5	10	20
10.5	10	17
11.5	6	12
12.5	6	5
13.5	7	6
14.5	7	2
15.5	3	2
16.5	4	2
17.5	3	1
18.5	3	1
19.5	2	1
Total	200	200

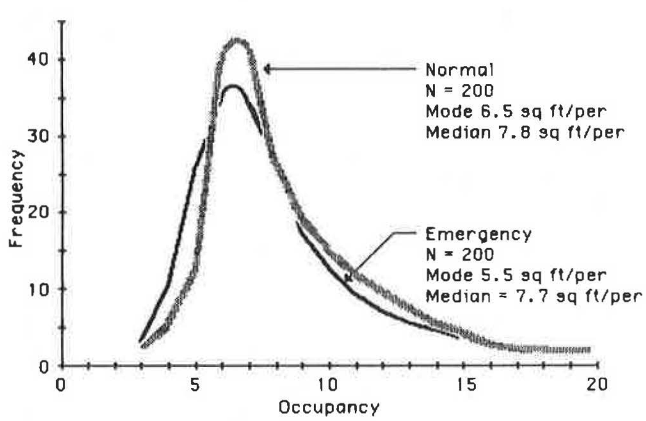

FIGURE 1 Personal space.

Speeds and Flows

The data given in Table 2 indicate the densities, speeds, and flows of pedestrians down the stairways under normal and fire emergency conditions. A maximum flow of 16.42 pedestrians per minute per foot-width was observed under normal conditions and a flow of 18.25 pedestrians per minute per foot-width was observed under fire emergency conditions. The highest density observed was about 0.29 pedestrians per square foot. In general, densities were found to increase in the lower stories of buildings. Figures 2 and 3 show these data graphically.

The highest speeds observed were 125 ft per minute and 137 ft per minute under normal and fire emergency conditions, respectively. Differences in the width of the stairways did not appear to cause changes in speeds or flows. Minor localized constrictions also had no apparent effect on speeds of flows.

Observations made during the emergency evacuations revealed that daytime evacuation exercises appeared to be carried out with less confusion than nighttime evacuations. Also, it appeared that, particularly at night and in spite of proper illumination, some crowding conditions on the stairways and passages tended to create hazardous conditions when occupancies were 3.5 ft^2 per person and less. It was also observed that nighttime evacuations created crowded conditions near the building exits at ground level and therefore choked the flow of evacuees trying to get out of the buildings. This situation could be hazardous in a real fire.

Cases of people tripping and falling on the stairways were rare. Such cases were confined to stairs that had riser heights of 7 1/2 to 8 in. and tread widths of 10 in. When a person tripped and fell, recovery was exceptionally fast.

Queuing at the entrance of stairways was observed in 25 percent of the evacuations, particularly in the lower stories of buildings, and lasted for a maximum of 25 sec. Most queues lasted for 5 sec and less. There were no apparent disruptions in evacuations due to queue formation.

No cases of fatigue were observed or reported during the exercises. It is reported that fatigue becomes a significant factor with severe adverse effects on people movement when evacuations down stairs exceed 5 min (8).

Some caution must be applied in interpreting and using the results because of the following factors:

1. These are preliminary findings based on a limited sample size.
2. The results are derived from simulated fire emergency exercises. These exercises were carried out without warning and therefore represent almost real conditions. A large majority of the evacuees interpreted the alarm and exercise as a genuine emergency.
3. Because the exercises were simulated there were no problems created by smoke and fumes. In a real fire, smoke and fumes would inhibit movement of stairway users and thereby reduce the capability of people to attain the speeds and concentrations indicated.
4. High-rise buildings with a range of configurations and characteristics were observed. There

TABLE 2 Pedestrian Movement Characteristics on Stairways

Occupancy, 1/k (ft^2/person)	Density, k (persons/ft^2)	Speed (ft/min) Emergency, V_E[a]	Normal, V_N[b]	Flow (person/min/ft-width) Emergency, q_E[c]	Normal q_N[d]
3.5	0.29	55	50	16.0	14.5
4.5	0.22	82	72	18.0	15.8
5.5	0.18	100	90	18.0	16.2
6.5	0.15	110	92	16.5	13.8
7.5	0.13	115	110	15.0	14.3
8.5	0.12	124	115	14.9	13.8
9.5	0.11	127	120	14.0	13.2
10.5	0.10	137	125	13.7	12.5
11.5	0.09	137	125	12.3	11.3
12.5	0.09	137	125	11.0	10.0
13.5	0.07	137	125	9.5	8.75

[a] $\bar{V}_E$ = 114.6, S = 26.6, and f_E = 178.
[b] $\bar{V}_N$ = 104.5, S = 25.4, and f_N = 191.
[c] $\bar{q}_E$ = 14.5, S = 2.7, and f_E = 178.
[d] $\bar{q}_N$ = 13.10, D = 2.3 and f_N = 191.

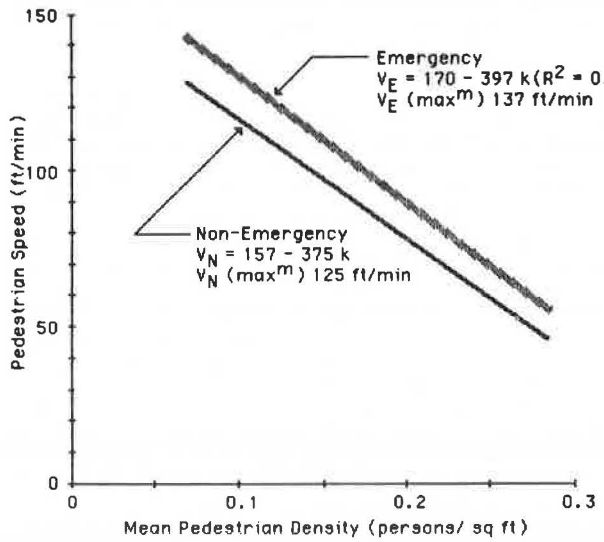

FIGURE 2 Speed/density.

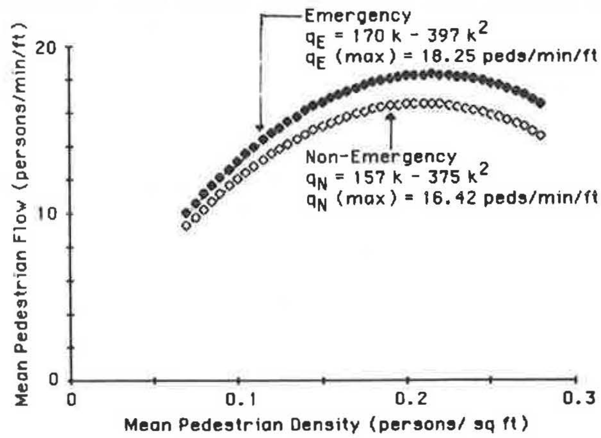

FIGURE 3 Flow/density.

were variations in landing widths, stair widths, tread-to-rise ratios, and egress routes. Added to this were social factors such as communication levels, social organization, and leadership qualities of fire safety officers and evacuees. These latter factors, although difficult to measure, should not be overlooked.

5. All of the evacuees were between the ages of 18 and 30. None of them were handicapped.

DISCUSSION OF RESULTS

A summary of results obtained from this study is compared with the findings of other researchers in Table 3. Pauls' work is of particular interest because of the extensive data base he used (4). His results appear to be compatible with those of this study. Galbreath's data and results on the relationship between concentration of people on stairs and forward movement appear to be rather overoptimistic (9). Fruin's results are for normal conditions and have been inserted in the table for quick comparison (2).

The London Transport Board (LTB) (10) determined, under normal conditions, that the flow rate of passengers in level passages (4 ft and wider) is 27 persons per minute per foot-width, and the flow down stairways was determined to be 21 persons per minute per foot-width. These values appear to be somewhat high. The LTB document also reports that maximum flows on stairways occur when personal space is 3 ft^2 per person. In comparison, the results obtained from this study indicate that the maximum flow of 18.25 persons per minute per foot-width occurs at an occupancy of about 5 ft^2 per person under fire emergency conditions; the corresponding figures for normal conditions are 16.2 persons per minute per foot-width at about 5 ft^2 per person.

From the literature on disaster and fire safety it is evident that the 22-in. unit (or module) has frequently been used for determining stairway and exit widths. Indeed building codes across the country have in general been greatly influenced by the 22-in. unit. It is therefore not surprising to notice the flow rate of evacuees specified traditionally in terms of the 22-in.-width-per-minute unit.

Pauls' remarks in connection with his Ottawa observations that "the 22 inch width concept cannot be justified on the basis of fairly discrete lanes of movement, as previously believed. In addition the conventionally accepted flow of 45 persons per min per 22 inch of stairway width appears to be over-optimistic by 50 to 100 percent or more, especially

TABLE 3 Comparison of Pedestrian Movement Characteristics

Condition	Researcher: Khisty, Normal	Khisty, Fire	Pauls, Fire	Galbreath, Fire	Fruin, Normal
Speed (ft/min) max[m]	125	137	100-140	158	128
Space (ft^2/person)					
Min[m]	3.5	3.0	3.5	2.5	–[a]
Mode	6.5	5.5	6.5		
Median	7.8	7.7	7.4		
Flow (ft/min/ft-width) Max[m]	16.42	18.25	16.36	23.45	20

[a]Level of service F, 4 ft^2 or less.

for mid-winter total evacuations in cold climates" (4). The "accepted flow" of 45 percons per minute per 22 in. of stairway in equivalent to 24.6 persons per minute per foot-width, which is at least 34 percent higher than the maximum flow observed in this study (4).

The "standard" unit (22 in.) for stairway and exit width has evidently been derived from the clearance width of adults. However, the width needed for walking adults is about 28 in. to account for body sway (8). "Body sway has been observed to range 1 1/2 inch left and right during normal free movement, and when movement is reduced to a shuffle in dense crowds and movement on stairs, a sway range of almost 4 inch has been observed. In theory this indicates that a width of 30 inch would be required to accommodate a single file of pedestrians traveling up or down stairs" (11).

The Life Safety Code developed by the National Fire Protection Association "is widely used as a guide to good practice and as a basis for laws or regulations. The code specifies the 'exit' in an overall definition of means of egress, and exits are measured in units of 22 inch width, taken from the average width of a man at shoulder height." In response to recent research on stairs "during both staged and normal evacuations the concept of a 30 inch width has been advocated" (11).

In a summary of life safety code provisions for occupant load and capacity of exits (Table 4) the number of persons per unit of stairs varies from 22 persons per unit width in hospitals to 75 persons per unit width in places of assembly. For residential buildings, such as dormitories, the capacity is 75 persons per unit width. This capacity translates to 41 persons per minute per foot-width and 30 persons per minute per foot-width if the unit width is taken as 22 and 30 in., respectively. These figures are 127 and 66 percent higher than observations made in this study and by Pauls (4). More recent work done by Pauls indicates peak flows of 30 persons per minute and mean flows of 24 persons per minute per unit of exit width down stairways (12,13). Egan gives several references (8,pp.185-187) in which the unit width is taken as 22 in., which results in person flows far exceeding actual observations.

This is a matter of serious concern and needs to be examined carefully in light of ongoing research.

TABLE 4 Summary of Life Safety Code Provisions for Occupant Load and Capacity[a]

Type of Establishment	Capacity of Stairs (no. of persons per unit width)
Places of assembly	75
Educational	60
Health care	22
Residential	75
Mercantile	60
Business	60
Industrial	60

[a]Extracted from Table 6-2c in Byran (11).

APPLICATIONS OF RESEARCH RESULTS

Some important research results of this study are

1. The traditional 22-in. width unit used in stairway design should by replaced by a performance-based width such as persons per minute per foot-width or persons per minute per meter-width.
2. A maximum pedestrian flow rate of 18 pedestrians per minute per foot-width should be allowed with space occupancies not less than about 5 ft^2 per person. An occupancy of 7.5 ft^2 per person is recommended.
3. Stairways must be wide enough for two people to descend side by side, thus improving the flow. This arrangement will help evacuate the aged or the infirm. The minimum width would be about 60 in. If a module is used at all, a 30-in. width per person is suggested.
4. Tread and riser dimensions should be uniform throughout the stairway. A minimum tread width of 11 in. (without nosing) and a maximum riser height of 7 in. are recommended.
5. Communication between fire control personnel and evacuees is important. Successful evacuation is heavily dependent on the use of a proper public address system that has the capability of conveying clear, audible messages.

Suggestions and recommendations for stairway design are in need of change as a result of studies done in recent years. The results provided in this paper can be transferred to stairways in theaters, arenas, stadiums, and other public buildings where stairways are a part of the pedestrian system.

SUMMARY AND CONCLUSION

This investigation consisted of measuring the personal space, speed, and flow of people descending stairways under two conditions, emergencies and normal everyday conditions. Observations were also made of the behavior of people during emergency conditions. It was found that current codes and regulations that address personal space and movement of people under emergency conditions are in need of revision, particularly because the design and operation of pedestrian facilities under disaster conditions are much more critical than they are under everyday, normal conditions. This investigation is justified on the basis of improving the development of safety regulations and design competence affecting the safety of human beings using stairways.

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Seattle Area HOV Lanes: Innovations in Enforcement and Eligibility

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ABSTRACT

Preferential high occupancy vehicle facilities such as lanes restricted for transit and carpools are playing an increasingly important role in urban transportation systems. The preferential treatment poses, however, new operational problems for state and local transportation departments and enforcement officials. The minimum occupancy requirement for carpools must be set and effective enforcement of the facility must be maintained. A demonstration project in Seattle, Washington, tested the use of a public telephone hotline to reduce transit and carpool lane violations and also introduced the use of a variable carpool definition in order to maximize transit and carpool lane effectiveness. The variable carpool definition was tested by lowering the occupancy requirements from three to two persons per vehicle at selected locations in an Interstate corridor. Project data showed a 33 percent reduction in transit and carpool violation rates attributable to the public hotline. The change in carpool definition occurred smoothly. Vehicle volumes increased at locations where the occupancy requirement was lowered. Violation rates did not increase at locations where the requirement remained at three or more persons per vehicle. The key to the success of both elements of the project was an extensive, well-orchestrated public information campaign.

During the last decade an increasing number of preferential high occupancy vehicle (HOV) roadway facilities have been built on the nation's urban freeways. These include designated HOV freeway lanes and on-ramp bypass lanes for vehicles with minimum occupancy requirements of two, three, or four persons per vehicle. HOV facilities are expected to play a greater role in the future in the more effective management of the urban transportation system. They offer a time savings that complements a wide range of other transportation services and incentives designed to encourage commuters to leave their cars at home; increase the use of carpools, vanpools, and transit; and raise the person-carrying capacity of urban freeways.

Preferential HOV facilities, however, pose new operational problems for state transportation departments and enforcement officials. The integrity and effectiveness of HOV facilities are threatened as more commuters ignore the lane restrictions. There is also a dilemma posed by opening an HOV facility and setting minimum occupancy requirements so high that relatively few vehicles use the facility or so low that the roadway soon reaches capacity. Variable minimum occupancy requirements are politically sensitive and call into question the traveling public's ability to understand vehicle occupancy requirements that change with time and geographic location within an urban area.

Both problems were the subject of an FHWA-funded HOV demonstration project conducted in Seattle, Washington. During 1983-1984, the Washington State Department of Transportation (WSDOT) together with the Washington State Patrol (WSP) and the Municipality of Metropolitan Seattle's Commuter Pool Division (Metro), tested some innovative, low-cost enforcement techniques and evaluated the effects of varying the minimum carpool occupancy requirement along different portions of the same Interstate corridor.

The results should be of particular interest to state transportation departments, enforcement agencies, regional planning agencies, local jurisdictions, and transportation agencies.

BACKGROUND

Interstate 5 (I-5) is Seattle's major north-south freeway. HOV lanes and metered ramp bypass lanes operate along a 12-mi stretch of I-5 to and from downtown Seattle (Table 1 and Figure 1). The HOV lanes are restricted to buses, vanpools, carpools, and motorcycles.

In 1981 six freeway on-ramps southbound and one northbound were reconstructed to provide a lane for vehicles with three or more occupants to bypass the signal controlling access to the freeway. A WSDOT evaluation of the system in March 1982 showed that between 9 and 38 percent of the vehicles traveling in the HOV bypass lanes carried fewer than the required three people.

The concurrent flow HOV lanes in north Seattle were constructed in 1983. The additional northbound lane extends 4 mi from the exit of the express lanes in the Northgate area to northeast 185th Street. The additional southbound lane extends 5 mi from 236th Street Southwest in Snohomish County to the Northgate entrance of the express lanes. In each case the lane is built on the far left, or inside lane, of the freeway.

The WSDOT's evaluation of the first 3 months of HOV lane operation (August 29 to December 6, 1983) showed that vehicles in the HOV lane save about 3 min and 20 sec southbound over the length of the HOV lane compared to general purpose traffic. The evaluation also showed that between 6 and 30 percent of the vehicles traveling in the HOV lane were violators carrying fewer than the required three people. During that same period the HOV lanes carried between 400 and 450 vehicles per hour during the peak commute periods. These volumes reflected only a 20 to 25 percent utilization rate of HOV lanes. The analysis also indicated that the number of people traveling in the HOV lane on I-95 during peak periods met or exceeded the number of people traveling in a general purpose lane:

	HOV Lane a.m. Peak Period (southbound)	HOV Lane p.m. Peak Period (northbound)	General Purpose Lane
Person trips	Up to 2,800	Up to 2,200	2,220-2,400

Continued monitoring by the WSDOT indicated that HOV violation rates were increasing. Surveys conducted in December 1983 and January 1984 showed that vehicles carrying fewer than three people comprised from 19 to 63 percent of traffic on the HOV ramp bypass lanes and from 13 to 50 percent on the concurrent flow HOV lane. The gradual deterioration in the system's integrity and perceived effectiveness led to a demonstration project to test new techniques to reduce violation rates. It also provided an opportunity to test the effects of varying the definition of minimum carpool occupancy.

METHODOLOGY

Enforcement

The enforcement element of the project tested alternatives to the high-cost approach of hiring additional law enforcement officers or paying overtime for special emphasis patrols to enforce HOV lane restrictions. The two alternatives tested were the 764-HERO public hotline and deployment of paraprofessional WSDOT observers.

Public Hotline

Before implementing this pilot project the WSDOT had received calls from the general public expressing concern about HOV lane violations. Although these

TABLE 1 HOV Facilities in I-5 Corridor

Direction	Description
I-5 Concurrent Flow HOV Lane	
Northbound	From express lanes' exit near Northgate to Northeast 185th Street
Southbound	From 236th Street Southwest in Snohomish County to the Northgate express lane entrance at Northeast 110th Street
	Express lane from Roanoke Street to downtown Seattle (Cherry/Columbia)
I-5 Metered Ramp HOV Bypass Lane	
Northbound	Northeast 45th Street
Southbound	236th Street Southwest (Snohomish County)
	Northeast 205th Street
	Northeast 175th Street
	Northeast 130th Street
	Northeast 85th Street
	Northeast 45th Street
Exclusive HOV Ramps	
Northbound and Southbound	Cherry/Columbia to and from the express lanes
Southbound	Pike/Pine to and from the express lanes

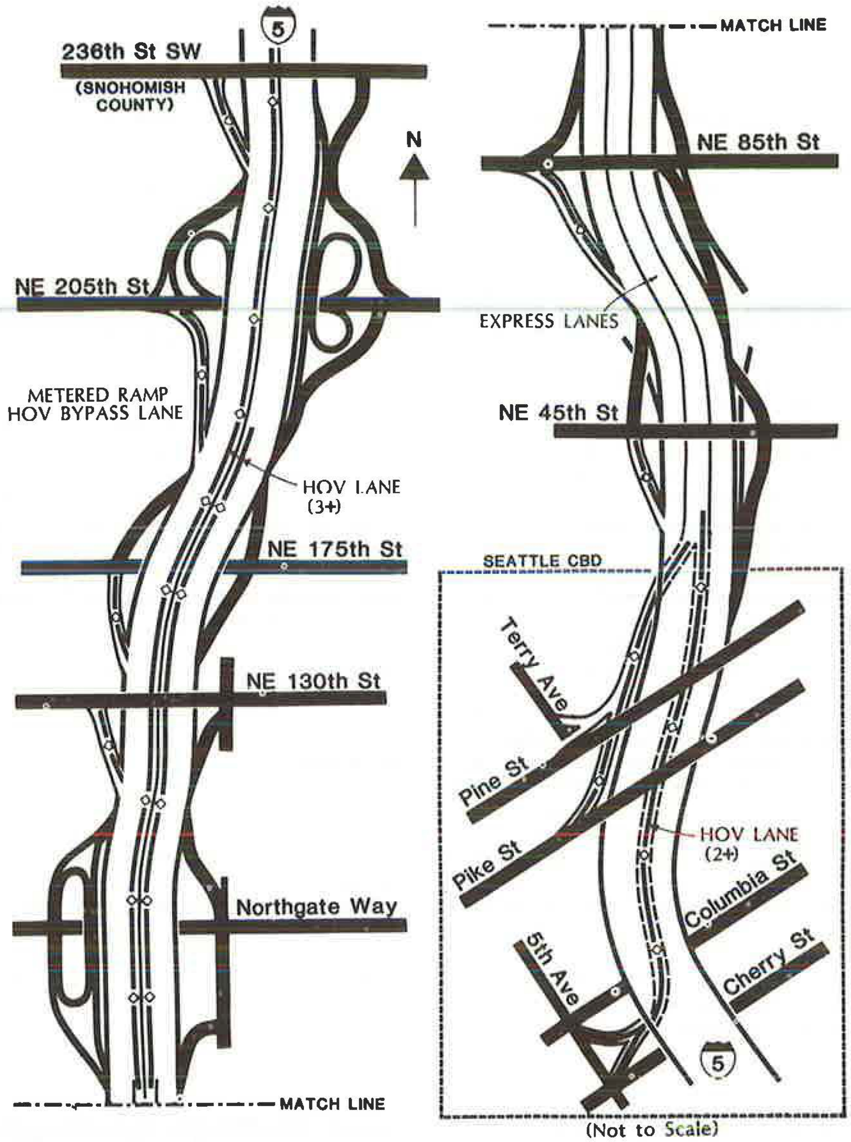

FIGURE 1 HOV facilities.

calls were infrequent, they demonstrated the commuting public's ability and willingness to share in the responsibility for enforcing the occupancy requirements of the HOV lanes. Before the pilot enforcement project, the WSDOT had not established a formal policy for handling reports of violations from the general public. WSDOT staff, however, did record information from the caller and transmitted that information to the WSP on an informal basis. This informal mechanism for handling citizen reports was the foundation for the HERO program.

HERO was patterned after the locally successful "Rat on a Rat" campaign aimed at apprehending bank robbers. The letters H, E, R, and O represent the last four digits of the phone number used by the general public to report HOV lane violations. Signs (Figure 2) announcing 764-HERO were installed, and an extensive public information campaign was undertaken to inform the public of the new program. WSDOT staff manned the HERO line from 6:30 a.m. to 6:30 p.m. (an answering machine was used from 6:30 p.m. to 6:30 a.m.) to obtain information on vehicles violating the HOV lane minimum occupancy requirements. Each caller was asked to supply the following information:

- Location of violation;
- Time, day, and date;
- Vehicle license number;
- Vehicle description (make, model, year, color, etc.);
- Number of persons in violating vehicle; and
- Other comments.

The caller was not required to provide his or her name when reporting violations. No record was kept of the caller's identity. The brochure, "Thanks For Being a HERO," however, was mailed to callers who desired more information about the program. The brochure briefly described the many transportation system management elements such as HERO, metered on-ramps, park-and-ride and pool lots, and vanpooling. Three hundred thirty-seven brochures were mailed during the study period.

DOT Observers

WSDOT staff also collected information on violations through field observations. Observation teams of one or two persons were assigned to specific ramps during

FIGURE 2 HERO sign.

peak periods. The teams observed vehicles using the HOV lanes and recorded information, identical to that asked of HERO callers, on vehicles that violated the minimum occupancy requirements of the HOV lanes.

When a violation report had been recorded from either the hotline or WSDOT observer, the accuracy of the license number and vehicle description were verified by comparing information from the violation report with the Washington State Department of Licensing (state DOL) vehicle registration files. Through interactive computing with the state DOL files, WSDOT staff obtained the registered owner's name and address as well as the make, model, and year of the vehicle. The vehicle description was then checked against the description provided by the HERO caller or WSDOT observer. If the descriptions matched, WSDOT staff proceeded to the first of four actions targeted at violators.

Owners of vehicles reported for the first time were mailed a "Signs of the Times" brochure. This brochure explained HOV enforcement and briefly described how the HERO project related to other transportation system management (TSM) activities that the WSDOT, Metro, and the city of Seattle were involved in, such as freeway on-ramp meters, park-and-ride lots, and destination carpool parking in downtown Seattle. The brochure also included a self-addressed, postage-paid rideshare application that could be completed and returned to Metro Commuter Pool for free computerized ridematching. During the 4 1/2-month project, 113 rideshare applications were returned for matching.

The WSDOT staff required approximately 3 days to process a reported vehicle's license number and to mail a brochure. One week was allowed to elapse before any further action was taken to make sure the brochure reached the registered owner and the driver had time to change behavior.

Owners of vehicles reported for a second time were mailed a second "Signs of the Times" brochure with a letter from the WSDOT. The letter detailed the time, date, and location of the violation and the license number of the violating vehicle. This personalized letter reinforced the brochure by emphasizing the need to comply with the HOV lane occupancy requirements.

Owners of vehicles reported for a third time received a letter from the WSP. This letter stated that WSDOT had notified the WSP that the owner's vehicle had been reported as repeatedly violating the HOV lane occupancy requirements. The letter also explained that if violators were apprehended they might be issued a summons that could result in a fine. During the study period the fine for an HOV lane violation was $37.

If continued violations were reported, the vehicle description, license number, and typical time and place of violation were forwarded to WSP. At WSP discretion, a trooper attempted to contact the registered owner of the vehicle.

The WSDOT used an in-house minicomputer for HERO data management. Three programs were developed. Program 1 allowed the operator to create a file for each reported license number. Data could then be entered on new violators and old violator files could be updated. Program 2, the statistics program, yielded detailed statistical data on various violation characteristics and patterns. Summaries could be compiled for the full HERO study period or for a specific period of time. Program 3, the purge program, extracted old violation records not needed to establish a pattern of specific violators. For this project, files that remained inactive for 6 months were purged.

Variable Carpool Definition

This project element had three primary objectives:

- Maximize the efficiency of the HOV facilities by increasing the number of vehicles traveling in the lane or ramp bypass,
- Attract more commuters to ridesharing, and
- Demonstrate that an HOV facility can operate under flexible carpool definitions with a high degree of public acceptability and without adversely affecting violation rates.

Three criteria were used to determine which sections of HOV lanes and metered ramps with HOV bypass lanes could have the minimum vehicle occupancy requirement lowered from three or more to two or more occupants per vehicle.

1. Peak period level of service (LOS) in the HOV lane had to remain at least two levels better than the LOS in the adjacent general purpose lane;
2. Increased HOV volumes, bypassing freeway on-ramp meters, could not impair the metering process by creating substantially longer queues and wait times for single-occupant vehicles; and
3. A main-line HOV lane and a metered on-ramp HOV bypass at the same location and in the same direction had to have the same minimum occupancy requirement; an HOV on-ramp bypass lane designated for two or more occupants per vehicle could not feed into an HOV lane on the adjacent main line with a carpool definition of three or more occupants per vehicle.

By using these criteria, the change from three to two ccupants in carpool definition was implemented along a 7-mi stretch of I-5 north at five metered on-ramps and the southbound HOV lane in the express lanes leading into downtown Seattle (Table 2).

Study Design and Data Collection

The project was designed to isolate and compare the effects of the two enforcement techniques and to

TABLE 2 Study Locations and Activities

Location	Direction	764-HERO Sign[a]	DOT Observer	Change in Definition of Carpool From 3 to 2	Counts
Ramps					
SW 236th Street	SB	Control ramp, no changes			X
NE 205th Street	SB	X			X
N 175th Street	SB		X		X
N 130th Street	SB		X		X
N 85th Street	SB			X	X
NE 45th Street	SB			X	X
NE 45th Street	NB	X	X		X
Pike/Pine Street	SB			X	X
Cherry/Columbia Street	SB			X	X
Cherry/Columbia Street	NB			X	X
Main Line					
N 110th Street	NB/SB				X
N 175th Street	NB/SB				X
NE 120th Street		X			
North of 145th		X			
South of 175th		X			
Between 236th and 205th		X			
NE 195th Street		X			
South of 185th Street		X			
South of Roanoke Street	SB[b]			X	

[a]All HERO signs on main line are located in median.
[b]Reversible express lanes.

detect any negative impacts of varying the carpool definition. Table 2 gives the enforcement activities conducted at each study location. HERO signs were posted on two ramps and at six main-line locations. WSDOT observers recorded violations at three ramp locations, one of which also had a HERO sign. The Southwest 236th Street ramp was designated as the control ramp; no enforcement activities were conducted at this location.

Field data were collected during a 9-month period from September 29, 1983, to June 30, 1984. The HERO line and changing the definition of a carpool from three to two persons at selected ramps and portions of the express lanes became effective February 14, 1984.

Peak-period ramp data were collected from 6:30 a.m. to 8:30 a.m. and from 4:00 p.m. to 6:00 p.m. Data on the main-line HOV lane were collected from 6:45 a.m. to 7:45 a.m. and from 4:45 p.m. to 5:45 p.m. Ramp data were collected on both the general traffic (if applicable) and metered ramp bypass lanes. Main-line data were collected only for the HOV lane. The WSDOT's routine monitoring of I-5 provided supplementary occupancy, volume, and speed data for all main-line lanes. These data were also used for evaluation.

Field data were organized on a spreadsheet. Calculations were made to determine vehicle volumes, number of person trips, average vehicle occupancy, number of violations, violation rates, compliance rates, and so forth.

Enforcement activity by WSP troopers along the I-5 north corridor remained constant. The number of troopers assigned to the corridor did not increase during the study period, November 1983 through June 1984.

Marketing and Program Information

The project team undertook and sustained an extensive public information campaign throughout the project. In preparation for the implementation of the enforcement activities and the change from three to two occupants, groups such as the Downtown Seattle Association (a local organization of more than 400 downtown business persons), various community organizations, the regional commuter pool network of more than 300 employee transportation coordinators, and pilots providing traffic reports, among others, received briefings, letters, posters, and news releases regarding the upcoming project. The team also undertook a direct mail campaign to 60,000 households near the freeway entrances with ramp designations to be changed from three to two occupants. The direct mail brochure alerted residents that beginning February 14, 1984, "two is all it takes" to use selected metered bypass lanes. This direct mail brochure included a postage-paid ride-match application. The project team also worked closely with local news media. Feature stories on HOV enforcement were aired on local television and radio news broadcasts. Prime time interviews with project team members were aired on radio, and feature stories, news releases, and public service announcements appeared in daily newspapers.

A letter was also sent to the Seattle District Court informing judges of the pilot enforcement project, its activities, and changes in carpool definition at selected locations. The project team anticipated some public confusion about the carpool definition that might potentially reach the district courts. For this reason the district court judges received the letter and a follow-up telephone call to answer questions about the project.

RESULTS

Violation Reports

From February 14 to June 30, 1984, 4,150 HOV lane violations were reported. The 764-HERO public hotline accounted for 89.5 percent of all reported violations. WSDOT observers accounted for 8 percent, and the remaining 2.5 percent were recorded by other sources.

First time violations accounted for 90 percent of all reports and resulted in distribution of 3,740 "Signs of the Times" brochures. Second time violation reports numbered 310, representing 7.5 percent of all violations reported. Three or more violation reports on the same vehicle accounted for the remaining 2.5 percent, and these were turned over to WSP to contact at their discretion.

Peak-period violation reports accounted for 63 percent of all reports, 44 percent representing violations in the morning (6:30 a.m. to 9:00 a.m.) and 19 percent representing afternoon violations (4:00 p.m. to 6:30 p.m.)

Single-occupant and two-occupant vehicles accounted for 64 percent and 30 percent, respectively, of all reported violations. The remaining 6 percent of the reports did not specify the occupancy of violating vehicles.

A majority of reported violations were for vehicles traveling on the I-5 main-line HOV lane. These reports totaled 3,360 or 81 percent of all violation reports.

I-5 metered on-ramp HOV bypass lanes accounted for 7 percent (300 reports), 5 percent (210) of all violation reports were for unspecified locations, and 7 percent (280) referred to violations that occurred in an HOV facility outside the project area.

Violation Rates

An HOV lane violation was defined as any vehicle, excluding motorcycles, traveling in the HOV lane with fewer than the required two or three persons.

Violation rates were determined by dividing the number of violations by the HOV lane volume and multiplying by 100. Compliance rates, calculated for ramps only, equaled the percentage of vehicles using both lanes of the ramp and adhering to the occupancy restrictions of the HOV lane. The compliance rates were calculated as follows:

Compliance rate = 100 - (HOV lane violations ÷ Total volume)

To evaluate the project's effectiveness in reducing HOV lane and metered ramp bypass lane violations, data gathered by field observers before February 14, 1984, were compared to those recorded by the observers after the HERO program and changes from three to two occupants were implemented. The overall violation rate, which includes all ramps and main-line study locations, decreased 38 percent from 28.1 to 17.4 percent. Several HOV locations, however, recorded fewer violations by virtue of the change from three to two occupants, which increased the number of commuting vehicles eligible to use the HOV facility. A more accurate account of the reduced violation rate would exclude data from those locations. When locations where the change from three to two occupants was made were omitted, the violation rate went from 28.5 percent before the enforcement project to 19.0 percent after, a 33.3 percent decrease. The difference was significant at the 95 percent confidence level (Table 3).

I-5 HOV Lane

I-5 HOV lane data were gathered at four locations, northbound and southbound at Northgate and at Northeast 175th Street. Northgate is the beginning of the southbound express lanes and the termination of the northbound express lanes. Likewise, the northbound HOV lane begins and the southbound HOV lane ends at Northgate.

Overall violation rates at the four observed main-line locations went from 28.3 to 19.1 percent, a 32.5 percent decrease in HOV violations. the project team conducted a statistical test on several categories to determine if the reduction in violation rates was significant. The results are summarized in Table 3.

As the data given in Table 3 indicate, two of the four observed main-line HOV lane locations showed significant reductions in violation rates. The Northeast 175th Street southbound violation rate went from 17.4 to 8.5 percent (a 51.1 percent decrease) and the Northeast 175th Street northbound violation rate went from 38.5 to 22.9 percent (a 40.5 percent decrease). The decrease in violations occurred even though overall volumes on I-5 (general traffic and HOV lanes) at 175th Street had increased by 13.7 percent southbound and 5.1 percent northbound over the average traffic volumes recorded before the enforcement activities began.

Violation rates of both southbound and northbound HOV lanes at Northgate showed no significant change. The southbound violation rate was 30.4 percent before and 28.2 percent after enforcement activities began, and the northbound violation rate was 15.4 percent before and 14.8 percent after. The ineffectiveness of the enforcement techniques at Northgate indicates how design and continuity of HOV roadway facilities affect commuter driving characteristics and compliance rates. In the southbound direction the commuter wanting to travel in the express lanes needs

TABLE 3 Before and After Violation Rates

Category	Before Violation Rate (%)	After Violation Rate (%)	Confidence Level (%)	Significant Reduction
All ramps and all main-line locations	28.1	17.4	95	Yes
Non-3-to-2 ramps and all main-line locations	28.5	18.9	95	Yes
All main-line locations	28.3	19.1	95	Yes
Northgate SB	30.4	28.2	95	No
Northgate NB	15.4	14.8	95	No
175th SB	17.4	8.5	95	Yes
175th NB	38.5	23.9	95	Yes
All ramps	27.3	12.3	95	Yes
Non-3-to-2 ramps	30.1	17.9	95	Yes

Note: Equation for testing a significant difference between the means of before and after HOV lane violations: If $\bar{X}_1 - \bar{X}_2 > K\sigma_D$, then the difference is significant.

$\sigma_D = (\sigma_1 2/N_1 + \sigma_2 2/N_2)^{1/2}$

where

$\bar{X}$ = mean,
K = critical value of t distribution,
σ = standard deviation, and
N = sample size.

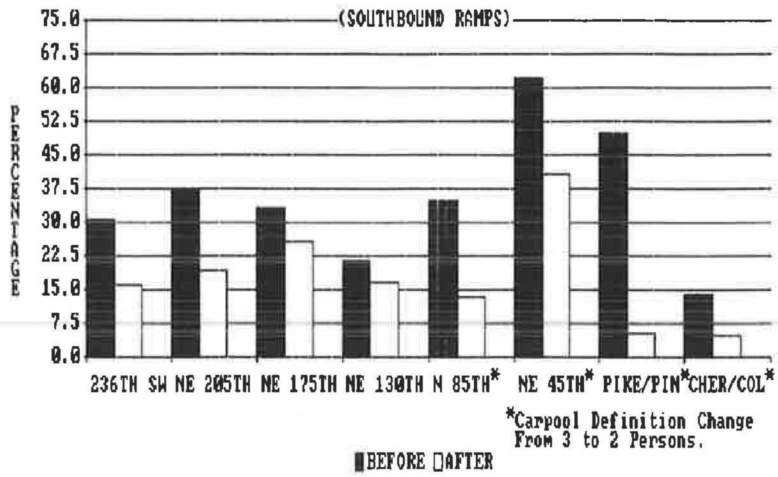

FIGURE 3 Before and after violation rates.

to position his vehicle in one of the two left (inside) freeway lanes, the furthest inside lane reserved for HOVs. To avoid missing the express lane entrance and possible accidents, the maneuver must be performed at a safe distance before entering the express lanes.

The consistent southbound HOV lane violation rates at Northgate indicate that the top priority for some commuters is to gain access to the express lanes. Adhering to the minimum occupancy requirements at this location appears to be less important and relatively inelastic with regard to enforcement.

In the northbound direction the HOV lane begins at Northgate where the general traffic express lanes end. Violation rates at this location were relatively low and remained unaffected by the enforcement actions. A plausible explanation for this is that these violators were not conscious that the HOV lane designation had begun and represented a core group that cannot be influenced initially by enforcement activities.

HOV On-Ramp Bypass Lanes

Overall ramp violation rates fell from 27.3 to 12.3 percent (a 55 percent decrease) after the pilot project enforcement activities were implemented. Again, the change from three to two occupants contributed to this reduction. The violation rate at ramps that had no change in occupancy restriction decreased 40.5 percent from 30.1 to 17.9 percent, and violations at the ramps for which the occupancy restriction was reduced from three to two decreased 61 percent from 24.1 to 9.4 percent. Figure 3 shows the before and after violation rates observed at each ramp included in the study.

Average automobile occupancy on the ramp HOV bypass lanes also changed after the project was initiated. Figure 4 shows how all southbound ramps north of Northgate registered an increase in average vehicle occupancy as a result of lower violation rates. South of Northgate, three of the four southbound ramps the carpool definition for which changed from three to two occupants showed decreases in automobile occupancy. This was caused by the addition of two-occupant vehicles to the HOV lane. Only the Northeast 45th Street on-ramp registered an increase in automobile occupancy. This occurred because the enforcement program reduced the ramp's high, 60 percent, single-occupant vehicle violation rate proportionately more than the increase in the two-occupant vehicles that used the HOV bypass as a result of the change from three to two occupants.

Comparison of Enforcement Techniques

As the project unfolded it became impossible to compare empirically the relative effectiveness of the

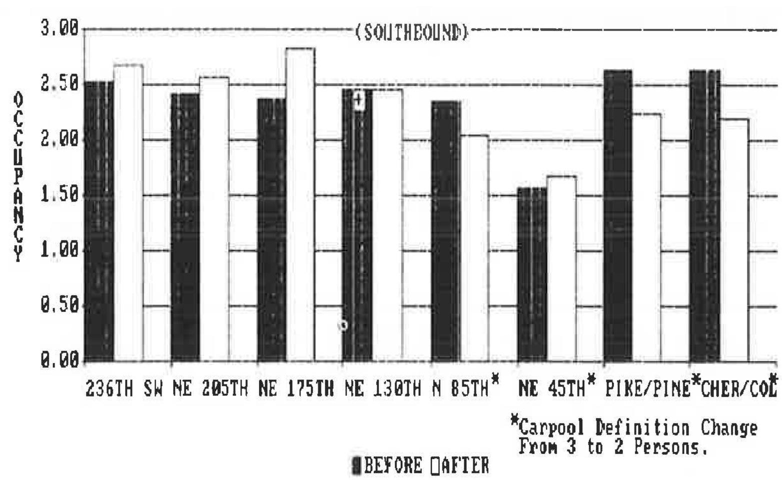

FIGURE 4 HOV lane average vehicle occupancy, without buses.

two enforcement techniques in reducing HOV lane violations. Media coverage and commuter familiarity with HERO signs resulted in hotline reports on violations for all the HOV facilities on I-5 and even on some HOV lanes outside the corridor.

For example, the southbound ramp at 236th Southwest in Snohomish County was the most northerly ramp included in the study. It was considered the study's control ramp. No enforcement activities (i.e., HERO signs or WSDOT observers) were implemented on this ramp. Eighty-five of the 300 reported ramp HOV bypass lane violations, however, referred to this location. The southbound ramp at 175th also had no HERO sign but had the greatest number of reported violations of any ramp.

The HERO hotline proved more accurate and cost-effective than the use of WSDOT observers. Of the HERO reports received, 84 percent provided license numbers and vehicle descriptions that matched the State Department of Licensing registration records. WSDOT observers provided accurate information in 77 percent of their reports. Project staff concluded that this difference occurred because the WSDOT observers were stationary whereas HERO reports came from motorists, including many carpools, traveling behind the violating vehicle.

The HERO element of the pilot project cost approximately $16,150 from February 14 to June 30:

Postage, materials	$ 1,500
Computer programming	4,000
State DOT staff (2 positions for 5 months)	10,500
Answering machine	150
Total	$16,150

The HERO line received approximately 50 calls per working day for a total of 3,715 calls providing correct information on violating vehicles. The cost was $4.35 per HERO violation report.

Public Opinion

In general, public opinion about the enforcement project was positive. Many HERO line callers were pleased that the WSDOT was taking steps to enforce the HOV lane regulations. WSDOT staff manning the HERO line noted that commuters were acutely aware of their commuting environment and eager to share experiences they encountered during their commute, HERO provided a mechanism for the public to participate in the enforcement of the HOV lanes and an outlet for commuter frustration generated by a feeling of helplessness when witnessing HOV lane violations.

During the course of the project, WSDOT staff noted that HERO line callers perceived a decrease in the number of HOV lane violations. Although no attempt was made to quantify the change in commuter perception, it nonetheless was an important indicator of the project's effectiveness. On the average, the WSDOT received one negative call or letter per day about the HERO program.

The media covered the pilot enforcement project extensively, particularly the 764-HERO hotline. Local newspapers carried several feature stories. Some articles raised a "Big Brother" image of the hotline, but the media attitude was positive and never branded the program as invasive.

Variable Carpool Definition

Each of the ramps for which the restriction was changed from three to two occupants showed an increase in HOV bypass lane volume as shown in Figure 5. This increase was due primarily to the addition of large numbers of two-occupant vehicles, as shown in Figure 6 for the southbound Cherry-Columbia ramp. Data were not available to determine how much of the increase in two-occupant vehicles came from existing two-occupant carpools shifting from other ramps and how many were new carpools.

Motorist confusion and higher violation rates did not occur in the corridor after the change from three to two occupants. The absolute number of two-occupant vehicles violating the HOV restrictions north of Northgate did not increase after the change from three to two occupants for the HOV facilities south of Northgate.

The project team held meetings with Seattle and Shoreline district court representatives. The Seattle District Court's jurisdiction extends north to Northeast 145th Street. The Seattle court handles between 600 and 700 traffic violation cases per month. Typically 5 to 10 percent of these cases are for HOV lane violations and this percentage did not change after implementation of the change from three to two occupants. Of the HOV lane violators requesting hearings after the change, 90 percent represented violations that occurred while passing another vehicle.

Shoreline District Court has jurisdiction over the project area from Northeast 145th Street to the King-Snohomish County Line and handles about 800 traffic-related cases per month. The Shoreline Dis-

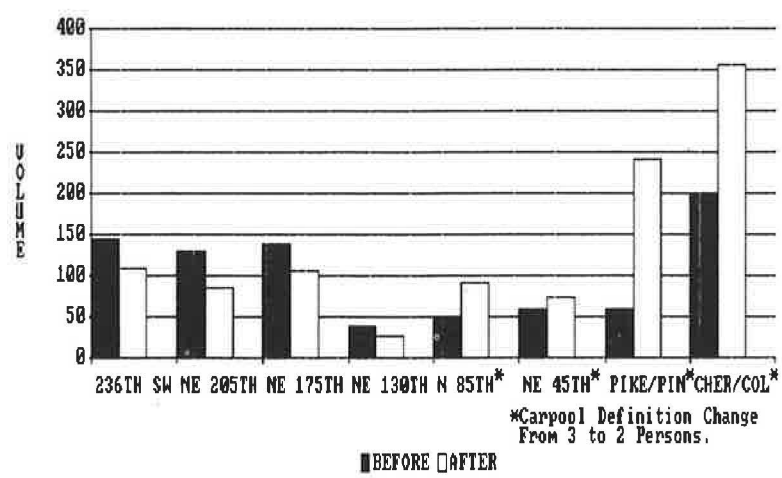

FIGURE 5 HOV lane volume, southbound.

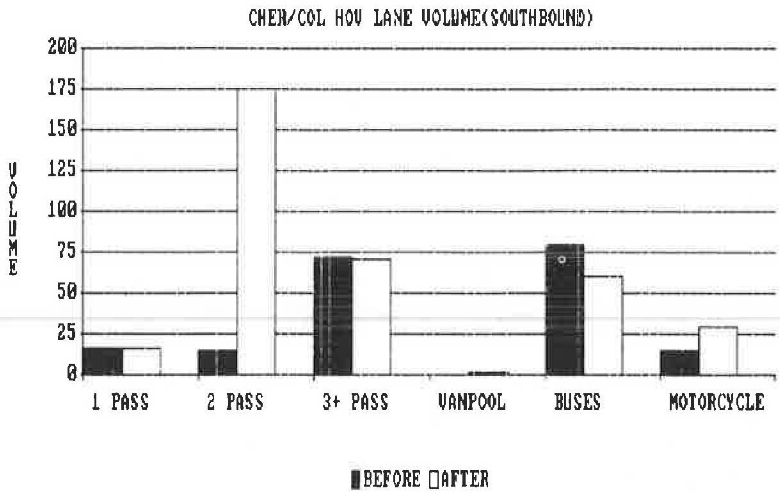

FIGURE 6 Cherry-Columbia HOV lane volume, southbound.

trict Court representative indicated that the variable carpool definition caused negligible confusion among those cited for HOV lane violations. The total number of HOV lane violations in January, 1 month before the pilot project was implemented, was 46. During May there were 44 HOV lane violations.

CONCLUSION

Overall HOV lane violations decreased by 33 percent and have remained low since the beginning of the project. Plans are for the WSDOT and Metro to expand the HERO program to all HOV lanes and ramps in the Seattle area.

The changes from three to two occupants in the I-5 corridor continue to operate smoothly. The WSDOT will analyze all future HOV facilities to determine if they can be designated for vehicles with two or more occupants.

The Seattle HOV enforcement and carpool eligibility project demonstrated that the commuting public can play an important role in directly improving compliance with roadway restrictions that give preference to high occupancy vehicles. The project also showed that motorists can adapt to changing carpool requirements within the same corridor.

The key to the success of both elements of the project was an extensive, well-orchestrated public information campaign. HERO was presented in a positive and upbeat manner, overcoming early skepticism about its "Big Brother" connotation. Extensive home-end marketing, advanced warning, and good signage succeeded in educating and informing the public about the change to a variable carpool definition in the corridor.

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