TRANSPORTATION RESEARCH
RECORD

No. 1375

Safety and Human Performance

Safety Research: Enforcement, Speed, Older Drivers, and Pedestrians

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1992

Transportation Research Record 1375
Price: $20.00

Subscriber Category
IVB safety and human performance

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Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
National Research Council. Transportation Research Board.

Safety research: enforcement, speed, older drivers, and pedestrians.
p. cm.—(Transportation research record ISSN 0361-1981; no. 1375)
ISBN 0-309-05418-4
1. Aged automobile drivers—United States. 2. Aged automobile drivers. 3. Traffic safety—United States. 4. Traffic safety. 5. Traffic regulations—United States. 6. Traffic regulations. I. Series.
TE7.H5 no. 1375
[HE5620.A24]
388 s—dc20 92-46874
[363.12′51] CIP

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Transportation Research Record 1375

Contents

Foreword

This Record contains research on several safety topics of concern in the United States and internationally. Driver noncompliance with traffic regulations and the amount of enforcement devoted to traffic are of particular concern in urban areas. Speed enforcement, characterization, estimation, and effects on accidents are continuing problems. Four papers in this Record address these issues. The older driver is of considerable interest, and research about older drivers is becoming more available. In this Record a method of identifying locations of high risk for older drivers is discussed. In addition, a paper on a topic little studied but much discussed, the older pedestrian, is presented.

Driver Noncompliance with Traffic Regulations in Rapidly Developing Urban Areas of Saudi Arabia

P. A. KOUSHKI AND A. M. AL-GHADEER

In spite of growing concern over the seriousness of driver noncompliance with traffic rules and regulations in the rapidly developing countries of the Persian Gulf region, the extent and magnitude of this problem has never been addressed. The results of a study of driver noncompliance with traffic regulations at 16 intersections in the capital and in a medium-sized urban area in Saudi Arabia are reported. A total of 7 hr per intersection, covering four daily peak and off-peak periods, was spent for data collection. Findings indicated that the problem of driver noncompliance with traffic control measures is, by far, greater than that observed in urban areas of the United States. Analysis of correlations was performed to examine degrees of association between violations and intersection size, location, land use (type and intensity), traffic volume, and time of day. Chi-square and *T*-tests were performed to ensure that the outcomes were not by chance. Time of day and volume of traffic demonstrated a significant relationship with traffic violations at intersections. Increased enforcement, improved level of awareness concerning safety implications, and modification of deficiencies in geometric designs were recommended as essential components of a comprehensive plan to improve driver compliance with traffic rules and regulations.

The results of a study aimed at quantifying the extent and magnitude of driver noncompliance with traffic rules and regulations in Saudi Arabia are reported. In the rapidly developing countries of the Persian Gulf, there is general agreement among the public and safety officials that driver noncompliance with traffic rules and regulations contributes significantly to the problem of road accidents. In Riyadh, Saudi Arabia, for example, over a period of 1 month in 1989, seven road traffic accidents occurred at one intersection, resulting in two fatalities, four disabling injuries, and significant property damage. High approach speed and noncompliance with traffic signals were cited as the major causes of these accidents (*1*).

The problem of violating traffic rules and regulations is not confined to developing nations. Driver disregard for traffic control devices has recently been recognized by the American Association of State Highways and Transportation Officials (AASHTO). In a nationwide survey conducted by AASHTO, it was found that 74 percent of the 46 responding states indicated that driver noncompliance with traffic control devices was a significant problem (*2*).

Review of the limited related literature on the subject indicates that the level of violation of traffic control devices is a function of several factors. These include the type and location of control devices, volume of traffic, time of day, and size of intersection. Stockton et al. (*3*), for example, found that traffic violations at stop signs have increased linearly since 1935. Berriott and Rorabaugh, in their study of driver violations at traffic signals, found that the violation rate, "not stopping when required," increased nearly five times when the traffic signal operation changed from regular (red, green, yellow) to flashing red (*4*). The configuration of traffic control devices has also been found to affect violation rates. For example, Kraft (*5*), studying the effectiveness of international symbol signs, found that the violation rate increased by a factor of five when a combination symbol/message sign was changed to a symbol sign without the message.

In a recent study, Gordon and Robertson (*6*) studied driver violations at 12 signalized intersections. It was found that most violations occurred at night at intersections with low traffic volumes. The study concluded that driver noncompliance was a significant problem and posed potential safety hazards.

The documentation of driver violations of traffic control devices in Saudi Arabia only dates back to 1984 (*7*). Analysis of these statistics, however, showed that the number of traffic violations nationwide increased by more than 260 percent over the 6-year (1984–1989) period. During the same time period, the number of reported road accidents increased by 23 percent. However, official statistics in Saudi Arabia do not necessarily provide an accurate picture. Studies indicate that the number of accidents (*8*) and accident fatalities (*9,10*) in Saudi Arabia may be underreported by as much as 60 percent.

Analysis of violation data by type revealed that high-speed violations have increased dramatically in recent years. Whereas other types of traffic violations—illegal parking, going through red, driving the wrong way, and illegal turning—have all generally remained constant over the last 2 years, the high-speed type of violation has more than doubled over the same 2-year period (*7*).

In spite of the seriousness of driver noncompliance with traffic rules and regulations and its significant contribution to severe road accidents in Saudi Arabia, the extent and magnitude of this problem has never been determined. This critical gap prompted the undertaking of this research study.

The objectives of this study were to (*a*) determine the type and frequency of violations at signalized intersections and (*b*) evaluate the causal relationship between intersection size, lo-

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cation, signal cycle length, approach volume, land use, time of day, and driver violations.

STUDY METHOD

Six tasks were established to achieve the stated objectives. The tasks included definition of violation type, selection of sample intersections, computation of sample observations, collection of data, data analysis, and, finally, evaluation of results.

Violation Type

On the basis of a review of official records and field observations, frequencies of five types of violations at signalized intersections were defined:

1. Going through red violation frequency (GTRVF), going through the intersection after the onset of the red indication (complete ignoring of a solid red indication);
2. Right turn on red violation frequency (RTRVF), making a right turn on red where such a turn is not permitted;
3. Starting on red violation frequency (SORVF), starting to move before the completion of the red phase;
4. Speeding on yellow violation frequency (SOYVF), speeding to go through the intersection during the yellow phase rather than stopping and waiting for the next green phase; and
5. High approach speed violation frequency (HASVF), approaching the intersection with speeds higher than the posted speed by at least 10 km/hr.

A sixth category of violation was defined as the sum of the previous five violation types (TOTVF).

For each of these violation types, a violation rate was computed by dividing the number of violations per 100 vehicles of its corresponding traffic volume.

Selection of Sample Intersections

The selection of sample intersections was based on a number of criteria. These included location within the urban area, number of approach lanes, land use type and intensity, and volume of traffic. A total of 16 intersections were selected for the study on the basis of these criteria and the time/budget resources of the project. Twelve of the intersections (1–12) were located in the capital city of Riyadh (population 1,400,000), and the remaining intersections were located in Buraidah, a provincial capital with a population of approximately 100,000, located 200 mi to the north of Riyadh. Both urban areas maintain a posted speed limit of 70 km/hr (43 mph).

Computation of Sample Observations

The minimum number of traffic observations for each intersection was computed using a statistical sample estimation procedure (*11*). The procedure computes a minimum traffic sample observation on the basis of a desired level of confidence (e.g., 95 percent, $\alpha = 0.05$) and an acceptable level of error (e.g., $e = 5$ percent). Assuming a standard deviation of $\sigma = 0.5$ (for the maximum possible error), the minimum number of required traffic observations was $N = 384$. The minimum observed hourly traffic volume for the sample intersections was nearly three times the minimum sample requirement.

Collection of Data

Data on physical and operational characteristics, traffic volume, traffic violations, and approach speed were collected at each intersection by a three-member study team. The volume and violation data were collected for 2-hr periods during the morning peak (7:00–9:00 a.m.), off peaks (2:00–4:00 p.m./8:30–9:30 p.m., a 1-hr period during the fasting month of Ramadhan), and the evening peak (6:00–8:00 p.m.), for a total of 7 hr per intersection. Data collection was carried out over a 4-month period, February through May 1990. The approach speed was monitored by radar. Dry pavement conditions and fair temperatures prevailed during the monitoring period.

At each intersection, traffic volume was counted on a rotation of 5-min intervals per approach for 2 hr. This resulted in a 15-min sample volume count per hour per approach. Simultaneously, all approaches were monitored for all traffic violations. Therefore, hourly volumes were computed by expanding the 15-min sample counts for each approach. Recorded violations represented total violations over the 2-hr period. This procedure is similar to that used by Gordon and Robertson (*6*). For monitoring large intersections with heavy traffic volumes, as many as six people were involved in the collection of data. The survey team included the same trained individuals throughout the study period to ensure consistency in the quality of the collected data.

RESULTS

The range, mean, and standard deviation of driver violations (by type) per observation hour, along with the number of violations per hour per intersection approach, are presented in Table 1. In an average hour, a frightening 31.4 drivers in Riyadh went through sample intersections during the red phase of signal operations. During an average observation hour, more than 264 drivers violated the no right-turn-on-red, nearly 20 drivers began moving before the completion of the red phase, more than 19 increased their approach speed (higher than posted speed) to clear the intersection during the yellow phase, and more than 11 drivers approached the intersection at high speed (10 km/hr in excess of posted speed). During an average hour, an alarming 346 drivers violated traffic signals and regulations. The range of violations shows that the most dangerous type of signal violation—GTRVF—may occur as many as 69 times during an hour.

In Buraidah, the violation frequencies were moderate compared with those for the capital city, Riyadh. In an average hour, more than 9 drivers violated the red phase (going straight through), more than 56 turned right on red where not per-

TABLE 1 Statistics for Violation Frequencies by Violation Type

	Violations per Hour			
Type	Range	Mean	Std.Dev.	per App.
(a) Riyadh				
GTRVF	14-69	31.4	14.7	7.9
RTRVF	97-615	264.3	185.9	66.1
SORVF	6-35	19.6	9.6	4.9
SOYVF	7-30	19.3	6.4	4.8
HASVF	2-29	11.3	5.8	2.8
TOTVF	45-736	346.0	212.1	86.5
(b) Buraidah				
GTRVF	5-14	9.2	3.6	2.29
RTRVF	27-79	56.5	21.4	14.1
SORVF	5-9	6.4	1.2	1.6
SOYVF	6-10	7.6	1.4	1.9
HASVF	5-8	6.0	1.1	1.5
TOTVF	48-109	85.7	24.3	21.4

mitted, and between 6 and 8 did not comply with other traffic rules and regulations. The traffic violation frequency in Riyadh was, on the average, between 3 and 4 times that of the city of Buraidah.

A violation rate was computed per 100 vehicles for each type of violation. The rates corresponding to GTRVF, RTRVF, SORVF, SOYVF, HASVF, and TOTVF are denoted as GTRVR, RTRVR, SORVR, SOYVR, HASVR, and TOTVR, respectively.

Table 2 presents the range, the mean, and the standard deviation of violation rates per hour of observation, as well as those per intersection approach per hour. As expected, the RTRVR violations were significantly more common than other types of violations in Riyadh. Nearly 18 out of every 100 drivers turned right on red where not permitted. The most dangerous violation type, GTRVR, was observed for 1.24 out of every 100 straight through vehicles. On the average, nearly 21 violations occurred for every 100 drivers entering the intersection.

The violation rate of traffic signals and regulations (for all categories of traffic violations) in Buraidah was nearly two-thirds those observed in Riyadh. However, the SORVR, SOYVR, and HASVR rates were much closer in the two cities. In fact, the violation rate for high approach speed was higher in Buraidah than in Riyadh, perhaps because of lower traffic volumes (higher level of service/higher operating speed) typical of small urban areas.

TABLE 2 Statistics for Violation Rates by Violation Type

	Violations Rate by Type per Hour			
Type	Range	Mean	Std.Dev.	per App.
(a) Riyadh				
GTRVR	0.44-4.82	1.24	0.55	0.31
RTRVR	0.07-23.1	17.40	4.24	4.35
SORVR	0.28-2.40	0.78	0.24	0.20
SOYVR	0.24-1.94	0.78	0.20	0.20
HASVR	0.08-1.90	0.45	0.23	0.11
TOTVR	1.10-34.1	20.70	5.12	1.71
(b) Buraidah				
GTRVR	0.74-1.30	0.93	0.10	0.23
RTRVR	4.03-5.41	9.50	0.22	2.38
SORVR	0.36-1.34	0.65	0.17	0.16
SOYVR	0.42-1.34	0.77	0.18	0.19
HASVR	0.36-1.12	0.60	0.15	0.15
TOTVR	5.91-10.5	12.50	0.59	1.08

Analysis of mean violation rates for each intersection indicated that three intersections in Riyadh experienced higher violation rates (22.6 mean TOTVR for the three intersections as opposed to 17.6 for the rest of the intersections). A comparison of physical, operational, land use, and volume characteristics of the study intersections showed that two variables clearly distinguished the three intersections with higher violation rates from the rest of the sample intersections: size and signal cycle length. In addition, one of the three intersections (Menamah) had a unique operational characteristic—one of its four legs was a one-way street, which usually encourages higher operating speeds (as seen by its HASVR of 0.60 versus the 0.45 average for all intersections). It is likely that the combination of large size and long cycle length (which are also dictated by design requirements) may also have a negative psychological impact on drivers, inviting more violations. Regular drivers, familiar with both the size and the longer cycle length, attempt to clear the intersection at any opportunity to avoid a long delay. The large size allows freedom of maneuverability.

Violations and Number of Approach Lanes

The study intersections were cross-classified by number of approach lanes (two, three, and four), and a mean violation rate (by violation type) for each group was computed. In Buraidah, all study intersections had two approach lanes. Table 3 presents that result. A prevailing characteristic among the violation rates was a general decrease with an increased number of approach lanes. For example, the most hazardous type of violation (GTRVR) decreased by 33 percent when the number of approach lanes increased from two to four. TOTVR decreased by 86 percent for intersections with four approach lanes. In Buraidah, the mean violation rates for intersections with two lanes were generally about one-half those of intersections in Riyadh. A similar trend was also found between the number of approach lanes and violation rates in a recent study in the Washington, D.C., area (*6*).

Violations and Cycle Length

In general, a slight increasing trend was found between the length of signal cycles and the violation rate. With the exception of HASVR, all types of violations reached their maximum rates at intersections with 80-sec cycle lengths, which accounted for 50 percent of sample intersections in Riyadh.

TABLE 3 Number of Approach Lanes and Mean Violation Rates by Type

No. of Approach Lanes	Mean Violation Rate by Type per Hour					
	GTRVR	RTRVR	SORVR	SOYVR	HASVR	TOTVR
2	1.68	18.4	0.90	1.0	0.92	22.2
3	1.60	22.4	1.0	0.90	0.46	26.4
4	1.12	0.27	0.60	0.74	0.34	3.1
2[a]	0.92	9.5	0.65	0.77	0.60	12.45

[a] Buraidah

In Buraidah, however, whereas the rates of violations for GTRVR, RTRVR, and TOTVR were nearly the same for the two cycle lengths, the rates of SORVR, SOYVR, and HASVR violations for shorter cycle lengths were nearly one-half those of longer cycle lengths. The natural tendency to avoid long delays at intersections may encourage drivers to violate rather than wait behind a long cycle length.

The analysis of violation rates by signal type (cantilever versus post) showed that no major trend existed between these two variables for sample intersections in Riyadh. In Buraidah, all signals were of the post corner type.

Violations and Intersection Location/Land Use

The rates for the most hazardous type of violation, GTRVR, and HASVR were higher in fringe areas (compared with the city center) in both cities. Lower traffic volumes (and the related lower social demand for appropriate driving behavior) and the low level of enforcement officials present (typical of fringe areas) may explain the higher rates of observed violations in these areas. The RTRVR in Riyadh was, however, significantly higher in the city center compared with that of the fringe area (21.6 versus 13.1). The rates for this type of violation in Buraidah were 8.6 and 7.9 for the city center and fringe areas, respectively. No major difference was found between the rates for other types of violations observed in city centers and fringe areas.

Intersections located in commercial land use areas experienced the lowest rates of all violation types compared with those of combination land uses and residential areas. Heavier traffic volumes and the more likely presence of enforcement officials in commercial districts may be the main factors causing this trend. The differences in the violation rate occurring in areas with combination and residential land uses were generally insignificant.

The violation rate in high-density areas of Riyadh was significantly smaller than those observed in low- and medium-density land use areas. This was particularly true for GTRVR (1.2 versus 1.8), RTRVR (13.0 versus 18.4), and TOTVR (16.0 versus 27.1). In Buraidah, no signalized intersections existed in the medium- or the low-density land use areas. Again, higher traffic volumes and enforcement official presence in higher-density land uses may explain the lower violation rates observed in these areas.

Violations and Time of Day

A clear picture appeared when violations data were analyzed with respect to time of day. The violation rates for every violation category were highest during the nighttime periods, second highest during the off-peak periods, and third highest during the peak periods. As presented in Table 4, the mean violation rates for the most dangerous type of signal violation—going through red—were 30 and 130 percent higher during the off-peak daytime and nighttime periods, respectively, than during the combined morning and afternoon peak periods. No significant difference, however, was observed in violation rates between morning and afternoon peak periods in Riyadh and Buraidah. The differences in TOTVR between the peak and the nighttime periods were nearly 58 and 20 percent for Riyadh and Buraidah, respectively. These findings are in close agreement with those of the Gordon and Robertson study (*6*).

TABLE 4 Mean Violation Rates and Time of Day

Time of Day	Mean Violation Rates					
	GTRVR	RTRVR	SORVR	SOYVR	HASVR	TOTVR
	Riyadh					
Morning/Afternoon: Peak-Periods	1.00	14.3	0.70	0.62	0.28	16.9
Off-Peak Periods:						
Daytime	1.30	16.3	0.76	0.86	0.52	19.7
Nighttime	2.30	21.1	1.18	1.22	0.94	26.7
	Buraidah					
Morning/Afternoon: Peak-Periods	0.80	7.8	0.64	0.76	0.60	10.6
Off-Peak Periods:						
Daytime	0.82	8.2	0.74	0.86	0.70	11.3
Nighttime	1.16	8.9	0.86	0.98	0.80	12.7

Violations and Traffic Volume

A category analysis was performed to examine the relationship between violation rates and traffic volumes. The result is presented in Table 5. The mean violation rates decreased significantly with an increase in traffic volume; this trend was true for all violation types in both cities. In Riyadh, for example, the mean of the most hazardous type of violation (GTRVR) decreased by 73 percent when the hourly traffic volume increased from less than 2,500 vph to more than 7,500 vph. The corresponding decrease in the mean GTRVR for Buraidah was more than 39 percent when hourly volumes increased from less than 1,000 vph to more than 2,000 vph. The corresponding decreases in the mean total violation rates for Riyadh and Buraidah were 53 and 29 percent, respectively. The decrease in violations with increasing traffic volumes fully supports the findings of Gordon and Robertson (*6*).

Analysis of Correlation

Both the frequency and the rate of violations were correlated with intersection-related, land use, time of day, and traffic volume variables. The resulting correlation coefficients further substantiated the study's findings. Both the sign and the

TABLE 5 Mean Violation Rates and Traffic Volume

Traffic Volume (VPH)	Mean Violation Rate by Type					
	GTRVR	RTRVR	SORVR	SOYVR	HASVR	TOTVR
	RIYADH					
< 2500	2.40	22.8	1.38	1.34	1.01	28.9
2500 - 5000	1.88	21.1	0.98	1.08	0.78	25.8
5000 - 7500	1.18	13.2	0.70	0.68	0.32	16.1
> 7500	0.66	11.50	0.58	0.50	0.22	13.5
	BURAIDAH					
< 1000	1.22	8.94	1.22	1.32	1.10	13.8
1000 - 2000	0.96	8.55	0.98	1.12	0.96	12.6
> 2000	0.74	7.70	0.44	0.54	0.42	9.8

magnitude of correlation coefficients generally conformed to expectations.

Violation frequencies for every type of violation were significantly and positively correlated with, in general order of significance, the time of day, the number of approach lanes, and the hourly traffic volume. Violations increased with an increase in the number of approach lanes, evening off-peak hours, and heavier traffic volumes. SOY and SOR violations demonstrated the highest correlations of all violation types with approach lanes (0.759 and 0.750, respectively), time of day (0.774 and 0.668, respectively), and traffic volume (0.639 and 0.647, respectively). Wider approaches provide for more freedom of maneuverability; night off-peak hours encourage all types of violations because of low traffic volumes and the presence of enforcement officials; and, finally, the higher the volume, the higher the frequency of violators.

A significant negative correlation was also observed between land use intensity and the frequency of high approach speed violations (−0.336). HASVF also increased with increases in cycle length (0.597) and during the night (0.330). The most hazardous violation (GTRVF) increased significantly with an increase in the number of approach lanes (0.638), cycle length (0.541), and volume of traffic (0.411).

The correlation coefficients for the rates of signal violations were also computed. Significant statistical correlations were found between violation rates and time of day (GTRVR, 0.463; RTRVR, 0.204; SORVR, 0.394; SOYVR, 0.557; HASVR, 0.544) as well as with traffic volume (GTRVR, −0.344; RTRVR, 0.489; SORVR, −0.373; SOYVR, −0.594; HASVR, −0.604). The rates for all violations at signalized intersections increased with time of day (higher rates of violations at night) and decreased with increasing traffic volumes (the heavier the traffic, the less the freedom to maneuver and consequently the less the opportunity to violate). The decrease in the freedom of maneuverability is particularly evident from the significant reduction in the rate of high approach speed violations. An increase in traffic volume is associated with a decrease in the level of service and vehicle headways, resulting in a decrease in operating speed.

A *T*-test was employed to test the null hypothesis (H_0: $r_{xy} = 0$, that the population correlation coefficient is zero). In other words, there is no statistically significant relationship between violations (frequency or rate) and such variables as the number of approach lanes, time of day, approach volume, and so forth.

A test of the hypothesis that $r_{xy} = 0$ is given by rejecting when (*11*)

$$|T| = \left|\frac{r_{xy}}{\sqrt{1 - r_{xy}^2}}\right| \sqrt{N - 2} \geq T_{\alpha/2;\, N-2}$$

where

$T_{\alpha/2;\, N-2}$ = percentage points of the *T* distribution,
r_{xy} = correlation coefficient between variables x and y, and
N = sample observations.

Results indicate that the null hypothesis (H_0: $r_{xy} = 0$) was generally rejected for all violation types and for most variables at the 95 percent significance level. Table 6 presents the results of the *T*-test performed on correlation coefficients between the mean violations (frequency and rate) and hourly approach volumes. With the exception of HASVF, the null hypothesis was rejected at the 95 percent significance level.

TABLE 6 Pearson's Correlation Statistics for Violations and Approach Volumes

Variable Name	Violations per Hour					
	GTR	RTR	SOR	SOY	HAS	TOTV
	(a) Frequency of Violations					
Correlation Coefficient	0.411	0.570	0.647	0.639	0.150	0.5767
T-test H_0:$r_{xy} = 0$	Rej.	Rej.	Rej.	Rej.	N Rej.	Rej.
R^2(%)	16.9	32.5	41.9	40.8	2.3	33.2
	(b) Rate of Violations					
Correlation Coefficient	-0.344	-0.489	-0.373	-0.594	-0.604	-0.480
T-test H_0:$r_{xy} = 0$	Rej.	Rej.	Rej.	Rej.	Rej.	Rej.
R^2(%)	11.8	23.9	13.9	35.3	36.5	23.0

Note: 95%, $\alpha = 0.05$
Rej = Rejected
N Rej = Not rejected

Coefficients of determination (square of coefficient of correlation) were computed to estimate the proportion of variations in violations explained by each contributing variable. For example, as can be seen from Table 6, the straight through volume explained 16.9 and 11.8 percent of the variations in the frequency and rate of going-through-red violations, respectively. The total hourly approach volume explained more than 33 percent of the variations in the total violation frequency and 23 percent of variations in the total violation rate. The approach volume also explained nearly 42 percent of variations in SORVF and more than 36 percent of variations in the rate of high approach speed violations. Similar findings were observed for time of day, signal cycle length, and number of approach lanes.

Statistical Significance of Relationships

The test of chi-square was used to examine whether differences in traffic violations at different intersections, with varied number of approach lanes, time of day, signal cycle length, and so forth, were statistically significant or chance. Results indicated that variations in all types of violation frequencies were statistically significant at the 99 percent significance level ($\alpha = 0.01$) for the number of approach lanes, land use (with the exception of HASVF), land use intensity, signal cycle length, and traffic volume.

The result of the chi-square test indicated that the frequency of violations increased at intersections with a larger number of approach lanes, higher intensity land uses, longer cycle lengths, and higher traffic volumes, as discussed before.

Violation Comparison

A comparison was made between traffic signal violations in Saudi Arabia and the United States. In a recent study (*6*), driver noncompliance with traffic signals was studied at 12 intersections in the Washington, D.C., metropolitan area. Comparisons were limited to reasonably compatible violations. The GTR violations in the U.S. study included the number of through and left-turning vehicles entering the intersection past the near curb line, and not necessarily going through the intersection after the onset of the red signal indication. In Riyadh and Buraidah, GTR violations are those in which the red signal indication was ignored.

Table 7 compares descriptive statistics for the frequencies of "going-through-red" and "right-turn-on-red" violations. The data clearly show that drivers in Saudi Arabia committed violations significantly more often than their counterparts in the United States. A clear difference also exists between driver violations in Riyadh and Buraidah. Whereas during more than 45 percent of the observation hours no violation of any type was committed by drivers in the United States, during 100 percent of the observation hours at the study intersections in Riyadh and in Buraidah at least one violation occurred.

The data also indicate that signal violations in Riyadh occur more frequently than in Buraidah. In addition to the smaller size, lower traffic volume, and lower congestion levels, the recent implementation of a strict enforcement of traffic rules and regulations in Buraidah was cited as a major factor contributing to fewer driver violations.

To obtain a more accurate picture of driver noncompliance, a comparative analysis was made between the rates of signal violations. As presented in Table 8, the mean rate for going-through-red violations in Riyadh is (at least) more than three times that of Washington, D.C., area studies, and the rate for right-turn-on-red violation is nearly nine times higher in Riyadh than in Washington, D.C. The rate for total violations in Riyadh is nearly 22 times that observed in the Washington, D.C., study. Similar trends exist in violation rates with regard to the time-of-day variable in Riyadh and Washington, D.C.

TABLE 7 Comparisons of Violation Frequencies

Variable Name	Violation Type					
	Going thru Red			Right Turn on Red		
	Riyadh[a]	Buraidah[a]	U.S.[b]	Riyadh	Buraidah	U.S.[c]
Range of violations per hour	24-69	5-14	0-11	97-615	27-79	0-8
Mean No. of violations per hour	31.4	9.2	4.9	264.3	56.5	3.4
Percent of at least one violation per total hour	100.0	100.0	54.3	100.0	100.0	48.7
No. of violations per approach per hour	7.9	2.3	1.2	66.1	14.1	0.84

[a] The number of vehicles completely ignoring the "solid" red phase and going through intersection

[b] The number of through and left-turning vehicles entering the intersection past the near curb line after the onset of the red signal indication (Ref. 6)

[c] Source: Ref. (6)

TABLE 8 Comparisons of Violation Rates

Variable Name	Mean Violation Rates (Violations per 100 vehicles)								
	Going Through Red			Right Turn on Red			Total Violations		
	Riyadh	Buraidah	US[a]	Riyadh	Buraidah	US	Riyadh	Buraidah	US[a]
Overall Mean Violation Rate	1.24	0.93	0.41	17.4	9.50	2.0	20.7	12.5	0.95
Time of Day: A.M./P.M. Peak	1.0	0.80	-	14.3	7.80	1.3	16.9	10.6	Low
Off-Peak/ Day	1.3	0.82	-	16.3	8.20	1.8	19.7	11.3	Med
Off-Peak/ Night	2.3	1.16	-	21.1	8.90	5.9	26.7	12.7	High

[a] Source: Ref. (6)

Summary and Conclusions

In an average hour at sample intersections in Riyadh, more than 31 drivers ran the red light, 264 drivers made an illegal right turn on red, nearly 20 drivers started to move during the red phase, 19 drivers sped up to go through the yellow phase when they should have stopped, and more than 11 drivers approached the intersection at high speed (significantly higher than the speed limit), for a total of 346 violations.

The frequency and rate of violations at signalized intersections for Buraidah were nearly one-half those for the capital city of Riyadh. The recently implemented program of stricter enforcement of traffic rules and regulations may be the main reason for the lower level of signal violations observed in Buraidah.

The frequency and rate of violations generally increased with an increase in signal cycle length. The natural tendency to avoid long delays at intersections may encourage drivers to violate rather than wait in a long signal cycle.

No clear trend appeared from the analysis of data concerning the relationship between the type of land use surrounding intersections and driver noncompliance with traffic regulations. This was perhaps because nearly all study intersections generally served a mix of land uses, and no intersection served a single type of land use. The intensity of land use, however, demonstrated a strong relationship with signal violations at study intersections. Low-intensity land use areas had significantly higher rates of traffic violations compared with high-intensity land use areas. Intersections serving low-intensity land use areas are characterized by low traffic volumes as well as low enforcement levels. These factors encourage violations.

The rate of violations at traffic signals was significantly affected by time of day. Nighttime was the period with the highest rate of violations. Off-peak hours were second, and morning peak hours had the lowest rates. This was true in both Riyadh and Buraidah, as well as in the Washington, D.C., area. Lower traffic volumes, more relaxed enforcement during the night, and driver exhaustion after a long day's work may be the main causes for the higher violation rates during off-peak and nighttime hours.

Traffic volume at intersections demonstrated the greatest influence on the rate of signal violations. As volume increased, a significant reduction in violation rates was observed. With increasing traffic volume, the opportunity to violate diminishes rapidly. This is mainly due to a reduction in the freedom to maneuver, an increase in the likelihood of accidents, stricter enforcement during periods with heavy traffic volumes, and, finally, a higher potential level of social and peer pressure on violating drivers.

A comparative analysis of signal violations indicated that drivers in Riyadh, in particular, committed a much larger number of traffic violations than their U.S. counterparts. This fact clearly demonstrates the need for improvements in the area of driver noncompliance with traffic rules in Saudi Arabia. The traffic fatality rate is nearly 17 times that of the United States (*8*). Responsible authorities should assign the highest priority to the problem of driver noncompliance.

RECOMMENDATIONS

The incredibly large number of road accidents in Saudi Arabia is a clear indication of the seriousness of driver noncompliance with traffic rules and regulations. Efforts should concentrate on the immediate implementation of a comprehensive program incorporating a significant increase in the level of enforcement, a concerted effort for the promotion of a multidimensional driver/public education program, and immediate action to eliminate engineering design deficiencies and remove hazards from roadways and intersections.

The public education campaign must be comprehensive, coordinated, and continuous. It should address all groups of drivers—public and official (who frequently violate traffic rules and regulations)—at all levels of formal education, and it should use all information systems and the media. Full coordination and cooperation of responsible agencies should be obtained to ensure maximum program effectiveness. The program should be continuous to address the continuously changing sociophysical environment.

In addition to geometric design of sight distances and channelizations, engineering design improvements should include the removal of unnecessary control devices, shorter signal cycles and signal progressions, and lighting of intersections that remain dark at night.

The problem of driver noncompliance in Saudi Arabia exists at all intersections—inside cities and in fringe areas, at large intersections and small ones, in residential and commercial areas, and at all times of the day. Attention, however, should be concentrated at night, at large intersections with low traffic volumes located at the fringe areas of city centers.

ACKNOWLEDGMENTS

The funding for this research was partly provided by the Research Center, King Saud University. The cooperation and support of officials in the General Traffic Directorate is also acknowledged. The authors thank Cynthia Owen and Bobbi Chouinard from the University of Alaska Fairbanks for editing and typing the manuscript.

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Publication of this paper sponsored by Committee on Traffic Law Enforcement.

Abridgment

Urban Traffic Enforcement: Candidate for Endangered Species List

JOHN J. COMPSTON, JR.

Traffic enforcement activities in urban areas are becoming the exception rather than the norm. Most of the seven cities in Ohio that have population in excess of 100,000 are experiencing decreases in traffic enforcement levels, and some of the decreases are sizeable. It is believed that the slide in traffic enforcement is a natural extension of what is happening in an urban society where violence, drugs, and fear prevail. When limited budgets prevent the hiring of additional law enforcement officers and requests for service, violent crime, and arrests are all increasing to record levels, law enforcement officers find little free uninterrupted patrol time. Hence, traffic enforcement suffers. No model as to how the atrophy affecting urban traffic enforcement can be corrected is offered. The scope of the problem is explained and the traffic safety community is challenged in hopes of generating future research and discussion.

In recent years, much activity has taken place in an effort to improve traffic safety. There has been legislation to increase penalties for the drinking driver and to mandate the use of seat belts. Engineers have produced vehicles better equipped to withstand a crash and roadways better designed to reduce crashes. Yet, in some areas, particularly urban, traffic enforcement has atrophied.

Urban traffic enforcement may well be a candidate for the endangered species list. This paper examines the state of urban traffic enforcement in seven Ohio cities, each with a population over 100,000. It is hoped that looking at urban traffic enforcement in Ohio will raise the consciousness of law enforcement and traffic specialists nationally, because the problem is not confined to Ohio.

URBAN VIOLENCE: A WAY OF LIFE

The mission of local law enforcement, in its oldest and simplest form, has been "to serve and to protect." If that is true, are not police shareholders in the gruesome traffic statistics that our nation produces? As death and suffering occur on the streets of our nation's urban centers, are not the police an integral part of the solution? Have urban law enforcement managers responded, or are they addressing a different kind of crisis?

Violent crime, much of it drug related, is on the rise in virtually every city in America. Urban neighborhoods in particular are disintegrating at an alarming rate as a never-ending cycle of confusion and mayhem seems to prevail.

Whereas the war on drugs may be having some success against casual drug use, the drug trade grows more deadly as drug traffickers struggle over turf and against stiffer competition. Guns, including more powerful paramilitary assault weapons, seem to be everywhere, many in the hands of the young and gang members with little fear of reprisal.

Against this backdrop, urban law enforcement officers prepare daily for what often becomes an 8- to 10-hr day of nonstop running from service delivery request to service delivery request, from crisis to crisis.

As society's members grow more concerned over the disintegration of their community through drugs, guns, and gangs, people demand relief from police agencies. To allay their fears, law enforcement managers align personnel to have the greatest effect on drugs and violence. As budget constraints have all but eliminated increases in manpower, managers will face difficulty in balancing the need to reduce fear, real or perceived, against other policing responsibilities.

STATE OF URBAN TRAFFIC ENFORCEMENT

These events have fueled the atrophy that has affected urban traffic enforcement. As the size of agencies remains static or shrinks, personnel readily available to respond to increased incidents requiring police assistance diminish. As a result, urban officers are hard pressed to find time for uninterrupted patrol functions of any type, much less traffic activities.

The idea that writing traffic citations is not real police work will also affect traffic enforcement. The dynamics of many urban areas are conditioning law enforcement officers to gravitate toward the criminal side of police work to the detriment of activities such as traffic. The Office of Judicial Statistics, Supreme Court of Ohio, has been recording record numbers of nontraffic cases arising out of Ohio courts. If not abated, this trend will perpetuate itself far into the future, as these perceived "real crime fighters" influence and eventually train new officers.

It is the thesis of this paper that the slide in traffic enforcement is a natural extension of what is happening in an urban society where violence, drugs, and fear prevail. When limited budgets prevent the hiring of additional law enforcement officers and requests for service, violent crime, and arrests are rampant (Tables 1 through 3), traffic enforcement does not receive anywhere near the media or community activists' pressure that other concerns receive. As a result, law enforcement managers give low priority to traffic enforcement. And as if on cue, law enforcement officers are less prone to concentrate on traffic enforcement even if some free time were available (Table 4).

Dayton Police Department, 335 W. Third Street, Dayton, Ohio 45402.

TABLE 1 Population Dispatches

	Population	1988	1989	1990	% Change 88-90
Akron	222,588	217,419	233,358	249,555	14.8
Cincinnati	372,282	199,045	218,916	230,307	15.7
Cleveland	523,906	369,400	409,688	437,584	18.4
Columbus	572,341	751,672	779,901	820,511	9.2
Dayton	178,866	284,346	352,946	375,522	32.1
Toledo	342,418	282,774	335,515	349,649	23.6
Yngstwn	101,642	N/A	79,558	90,859	14.2

Source: Planning Bureau for Each Department

A CHALLENGE FOR THE TRAFFIC SAFETY COMMUNITY

Absent a dramatic collision, the situation urban areas have found themselves in will ensure urban traffic enforcement's place on the endangered species list until it eventually falls into the extinct category. This paper's intent is to call attention to this problem and to challenge law enforcement managers, transportation specialists, traffic safety managers, and others to abate this slide toward extinction.

Several areas need further research and discussion. Criminal activity data are collected and recorded through the Federal Bureau of Investigation's Uniform Crime Reports. This method allows for consistency of data collection and some restricted comparisons from community to community. A similar method for traffic accident/enforcement data is necessary on a national basis.

One method of policing generating continued research and experimentation is problem-oriented policing. This method is a departure from the traditional policing methods of incident-driven responses. Problem-oriented policing looks at incidents as symptoms of a larger underlying problem and attempts to solve the problem, thus reducing incidents. Using this approach, police and traffic engineers would work in concert to develop abatement strategies at high accident/fatality locations.

TABLE 2 Violent Crime

		Murder	Agg Asslt	Rape	Rob.
	1988	30	1170	150	662
Akron	1989	20	1307	179	745
	1990	18	1600	193	773
	1988	47	1645	296	1475
Cincinnati	1989	45	1866	351	1509
	1990	49	2426	388	1613
	1988	137	2557	844	3795
Cleveland	1989	144	2939	837	4045
	1990	168	3259	846	4917
	1988	69	2111	594	3028
Columbus	1989	90	2226	543	3127
	1990	89	2745	647	3541
	1988	44	980	264	1648
Dayton	1989	53	1068	306	1459
	1990	47	1246	321	1475
	1988	n/a	n/a	n/a	n/a
Toledo	1989	41	1273	392	1583
	1990	37	1334	422	1748
	1988	26	n/a	77	381
Youngstwn	1989	19	348	72	386
	1990	19	644	64	580

Source: FBI Uniform Crime Reports

TABLE 3 Arrests

	1988	1989	1990	% Change 88-90
Akron	10,478	10,345	10,950	4.5
Cincinnati	30,038	30,513	36,646	21.9
Columbus	19,515	14,035	13,558	-30.5
Cleveland	34,425	39,026	43,795	27.2
Dayton	19,654	21,613	21,302	8.4
Toledo	N/A	22,199	24,004	8.1
Youngstown	N/A	6,365	6,939	9.0

Source: Planning Bureau for Each Department

However, a glitch that will affect problem-solving policing efforts and a national traffic accident/enforcement data collection system is the emerging trend by some law enforcement agencies to no longer investigate property damage accidents in an attempt to reduce calls for service. This could skew all traffic accident data and complicate an already inaccurate and inconsistent informal data collection system.

There is a great need to explore the impact of traffic enforcement on criminal activity. Folklore seems to indicate that strict law enforcement activity will have a positive impact on reducing some property crimes. However, no academic research studies have delved into this area. Further research should attempt to correlate traffic enforcement and the reduction of violent crime, drug activity, and the perception of fear within the urban community. Such efforts could raise the priority given to traffic enforcement in urban areas.

Traffic enforcement training needs to be strengthened. Most training curriculums have few hours of traffic-related instruction compared with other subjects. This influences officers to believe that traffic enforcement is not a high priority within the agency. Giving traffic a higher priority in training curriculums will increase the awareness that traffic enforcement is still a critical component of the law enforcement mission.

With the swift advancement by private for-profit corporations into areas that were once reserved solely for public justice systems, could privatization of urban traffic enforcement be in the offing? Profit-oriented corporations now run prisons, conduct private undercover drug investigations for municipalities, and provide rent-a-judge-and-jury to settle some

TABLE 4 Traffic Enforcement Levels

		1988	1989	1990	% Change 88-90
Akron	Citations	43,869	36,906	35,619	-18.8
	DUI Arrest	1,688	1,537	1,719	1.8
Cincinnati	Citations	292,031	264,754	270,166	-7.5
	DUI Arrest	6,001	6,334	6,608	10.1
Cleveland	Citations	101,687	97,481	113,105	11.2
	DUI Arrest	3,347	3,571	4,553	36.0
Columbus	Citations	118,551	116,394	115,599	-2.5
	DUI Arrest	n/a	n/a	n/a	
Dayton	Citations	37,173	26,998	22,492	-39.5
	DUI Arrest	1,218	1,045	1,109	9.8
Toledo	Citations	51,947	48,693	40,920	-21.2
	DUI Arrest	2,951	2,870	3,157	6.9
Yngstwn	Citations	13,295	10,893	15,923	19.8
	DUI Arrest	1,182	929	863	-27.0

Source: Judicial Statistics, Supreme Court of Ohio civil disputes. Some more affluent neighborhoods in urban areas now contract with private security firms to provide additional police services to their community, even when public policing is available. Contracting private security corporations for traffic enforcement and accident investigations could be a way for some neighborhoods to fill the void in urban traffic enforcement. Is the contracting of private judges and juries to hear traffic cases such a remote idea, since public court dockets and jails are already unable to keep pace with criminal cases? Since much of society believes that the private sector is more efficient, these ideas are probably closer than we think.

As our society becomes increasingly violent, continued pressure will be directed at law enforcement managers to loosen the vise of fear that has seized much of society. Currently, urban law enforcement managers' response to this plea is at the expense of traffic enforcement activities. To reduce the mounting losses from traffic accidents, urban traffic enforcement must be a critical component of any strategy, complementing the efforts in engineering technology and legislative initiatives.

The time for decisive action is now. Failure to respond to the atrophy that has affected urban traffic enforcement will surely guarantee it as a candidate for the endangered species list.

Publication of this paper sponsored by Committee on Traffic Law Enforcement.

Feasibility of Photo-Radar for Traffic Speed Enforcement in Virginia

CHERYL W. LYNN, WAYNE S. FERGUSON, AND NICHOLAS J. GARBER

Because of increasing difficulties in enforcing speed limits on high-speed, high-volume roads, it was proposed that experiments be conducted with photo-radar to determine whether using it could help reduce average speed and speed variance. It has been widely used in Europe for about 30 years and very recently used in the western United States. A project task force led by researchers from the Virginia Transportation Research Council conducted site visits to cities in Europe and the United States where photo-radar is being used. The task force also invited five manufacturers of photo-radar equipment to demonstrate their equipment during a 2-week series of tests on sections of U.S. Interstate highways with varying volumes of traffic and differing traffic characteristics. The tests were designed to provide the researchers with data on the accuracy, reliability, and efficiency of each unit and help them determine whether photo-radar could be successfully deployed as an enforcement tool on high-speed, high-volume roads. The researchers concluded that four of the five photo-radar units tested in the study met the minimum standards for accuracy, reliability, and efficiency established by the evaluators in conjunction with the project task force and therefore recommended efforts to pass enabling state statutes and test further the efficacy of using photo-radar under actual traffic-enforcement conditions.

Speeding on high-speed, high-volume highways continues to be a serious problem in the United States. The expansion of roadways to up to eight lanes in response to increasing traffic has reduced and sometimes eliminated the shoulder area traditionally used for roadside ticketing of speeders. The size and capacity of these roadways add to the problem. This is especially true on the Capital Beltway (I-495) around Washington, D.C., where more than 60 percent of the drivers exceed the speed limit.

Because of increased speeds and the resulting increase in incidents on the Capital Beltway, the Departments of State Police and Transportation in Maryland and Virginia, in cooperation with the Federal Highway Administration and the National Highway Traffic Safety Administration, instituted a feasibility study of the use of photo-radar for speed enforcement. The study was conducted by the Virginia Transportation Research Council (VTRC) for the Virginia Department of State Police.

Photo-radar equipment combines a camera and electronic controls with a radar unit that detects speeding vehicles. The various configurations in which photo-radar may be operated are shown in Figure 1. It can be operated in a stationary mode mounted on a tripod, in a cabinet, on a pole on the side of the roadway, on an overhead structure, or in the back of a motor vehicle. Some types of photo-radar can be operated in a mobile mode, installed in the dashboard area of a vehicle to take pictures of speeding vehicles as they approach or pass. If deployed to photograph oncoming traffic (see Figure 2), once the unit's radar detects a speeding vehicle, the unit's camera photographs the driver's face and front license plate. If deployed to photograph receding traffic, the camera photographs the rear license plate. At least one manufacturer's unit can photograph in both the oncoming and receding modes through use of an additional camera, which is activated by the flash unit of the primary camera.

The radar used in photo-radar equipment operates on the same principle as the radar used by police in everyday speed enforcement. This principle, called the Doppler effect, is the apparent change in the frequency of a sound wave resulting from the change in the distance between the "listener" and a moving object. The radar unit sends out sound waves of a given frequency that bounce off the moving vehicle and are received by the radar unit. By measuring the change in frequency over a given time period, the distance traveled is measured and the speed of the vehicle is calculated. After the license number of the speeding vehicle is determined from the photograph, a citation is sent to the registered owner of the vehicle. If the owner was not the driver, the owner may avoid liability for the ticket by identifying the driver.

Traffic Monitoring Technologies (TMT), located near Houston, Texas, is the only manufacturer of photo-radar equipment in the United States. TMT equipment is currently being used in Pasadena, California, and Paradise Valley, Arizona. The other five principal manufacturers are located in Western Europe and Scandinavia, where photo-radar equipment has been used for more than 30 years, and Australia.

METHOD

The researchers sought to evaluate the feasibility of photo-radar use on the Capital Beltway through four methods:

1. Outline the history and acceptance of speed enforcement technology and address the constitutional and evidentiary issues presented by photo-radar use (not discussed in this summary document).
2. Make site visits to the two cities in the United States where photo-radar technology has been used in speed enforcement and to four European manufacturers of photo-radar equipment.

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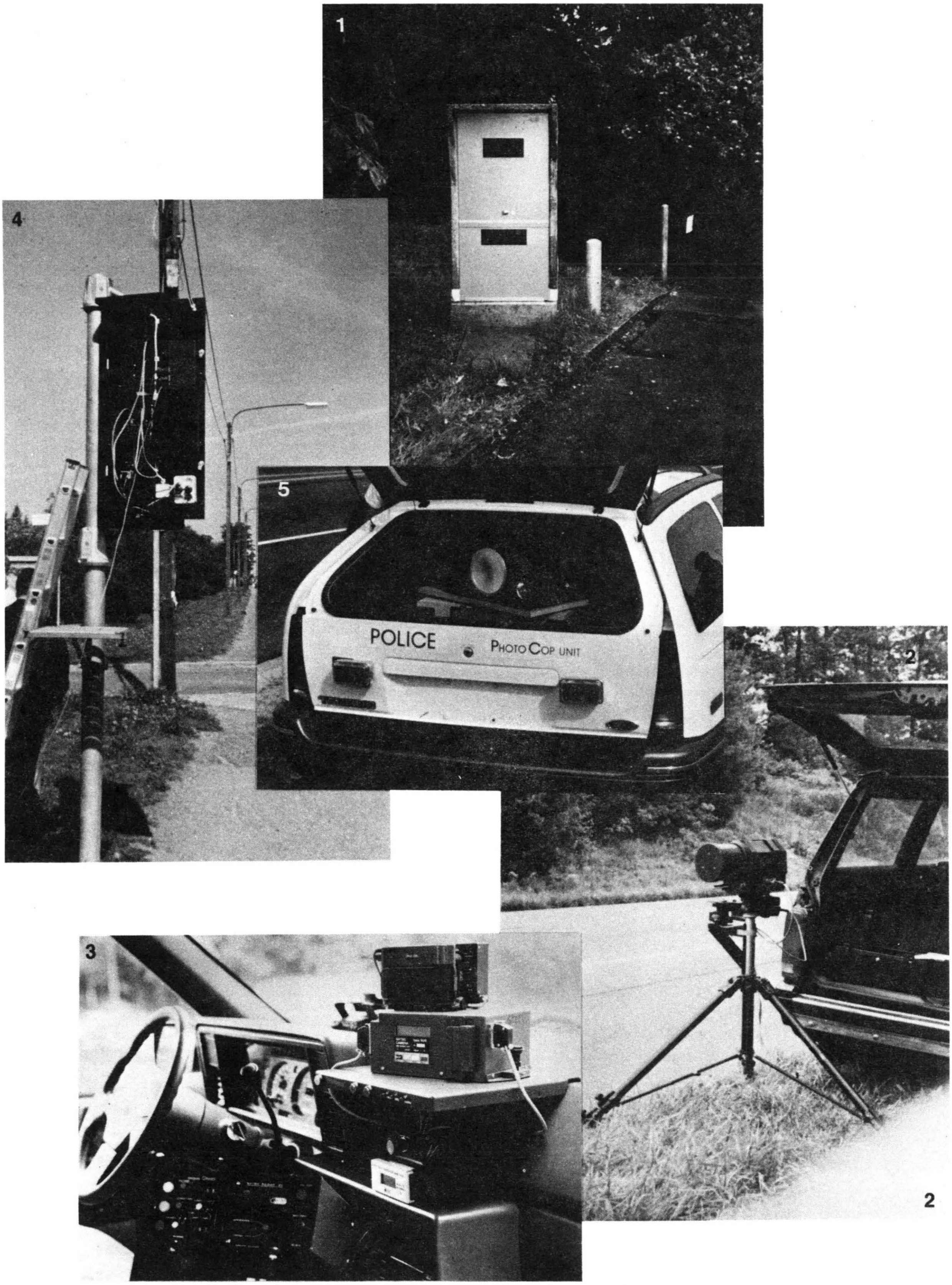

FIGURE 1 Modes of photo-radar operation.

FIGURE 2 Typical photograph produced by a photo-radar unit. License plate number was deleted to ensure the privacy of the vehicle's owner.

3. Test photo-radar equipment on selected highways in Virginia and Maryland.
4. Conduct an opinion survey to measure public sentiment concerning the potential use of photo-radar on the Capital Beltway.

The study culminated in a report entitled *Automated Speed Enforcement Pilot Project for the Capital Beltway: Feasibility of Photo-Radar*, from which this summary is drawn. (A more detailed discussion of the issues presented in this paper is available in that report, available from VTRC.)

RESULTS

Site Visits

From February 26 to March 5, 1990, site visits were made to Pasadena, California, and Paradise Valley, Arizona, where photo-radar leased from TMT is currently used in speed enforcement. Between May 20 and June 2, 1990, the facilities of four European manufacturers of photo-radar were visited: Gatsometer (the Netherlands), Multanova (Switzerland), Traffipax (Germany), and Trafikanalysis (Sweden). The manufacturer in Australia—AWA Defence Industries—was not visited because of budgetary constraints.

The purposes of the site visits were to review and discuss the equipment on site with its users and manufacturers, observe the equipment in use at locations where the manufacturer believed it had been used successfully, compare the equipment with the manufacturer's claims, and evaluate its potential for effectiveness on a congested urban highway such as the Capital Beltway.

Pasadena, California

Confronted with speed-related problems arising from heavy commuter traffic through residential neighborhoods, Pasadena, a city of 130,000, commenced the testing of photo-radar in 1987 in speed zones of up to 50 mph. Photo-radar is currently used on highways with three or fewer lanes. Approximately 45 percent of drivers ticketed by photo-radar pay the fine without attending court, nearly 32 percent of drivers choose traffic school, and about 7 percent of the cases are dismissed.

However, 16 percent of those cited ignore the ticket. Moreover, those who ignore the ticket suffer no consequences because the administrative cost of issuing a summons for a photo-radar violation in Pasadena is too high. Police fear that this may eventually undermine the program. TMT leases the photo-radar equipment to Pasadena for a fee of $20 per conviction. However, the Pasadena program does not pay for itself because of a low fine schedule and the use of attending traffic school as an alternative to fines.

Paradise Valley, Arizona

Paradise Valley, a town of 14,000, has a high volume of speeding commuter traffic. Photo-radar has garnered community, judicial, and media support. Estimates suggest that citation rates for photo-radar are 19 times greater than for mobile patrols. Citations are mailed within 2 weeks of the offense, and if the offender challenges the citation, a photograph is developed for trial. At trial, if the driver photographed is not the owner, the owner is requested to identify the driver under oath. If the owner identifies the driver, a citation is issued to the driver within 30 days of the offense, satisfying due process requirements. If the owner refuses to identify the driver, the owner can be held in contempt. However, to protect the public image of the photo-radar project in Paradise Valley, this option is rarely used.

Paradise Valley, unlike Pasadena, discounts the threat presented by ignored citations. The authorities may issue a summons immediately to those who disregard citations. Moreover, Paradise Valley authorities suspend the vehicle owner's license indefinitely if the summons is ignored. Speeds on most roads have decreased, and local officials believe that photo-radar has freed more police time for enforcement of alcohol-related violations. Furthermore, police officers assert that once they gained experience concerning the locations and times at which photo-radar is most effectively used, the percentage of usable photographs increased. TMT services the program in Paradise Valley at a fee of $20 per conviction. Fines generated from photo-radar convictions exceed the costs of the program itself, providing a source of revenue for the Paradise Valley community.

Western Europe and Scandinavia

Photo-radar has been used in Western Europe for about 30 years and in Scandinavia for about 5 years. Although one brand of photo-radar equipment has been used on a high-speed, high-volume roadway (i.e., the Autobahn in Elzberg, Germany), photo-radar is used in basically the same manner as in the United States—on relatively low-volume, low-speed surface streets. Most manufacturers cite success stories in which photo-radar use resulted in reduced speeds or reduced accidents.

Capabilities of Equipment

Table 1 summarizes the capabilities of the equipment manufactured in the United States and overseas. The equipment made by AWA Defence Industries is included in the table. Although no site visit was made to Australia, AWA participated in the field demonstrations in the United States, thereby providing the researchers with the pertinent information.

All of the equipment can operate in a stationary mode. All of the units can operate at night using a strobe. Three of the six units can monitor traffic while being operated in a moving vehicle. Five of the six units can monitor oncoming and receding traffic at the same time, although this feature is rarely used. Finally, and most important for states like Virginia that have a separate speed limit for trucks, four of the six photo-radar units can enforce one speed limit for passenger vehicles and another for large trucks.

Add-ons and attachments are available for use with photo-radar. All manufacturers offer a computer interface and software that will analyze the speed data collected on site. Video is also available for on-site use. One of the more interesting peripherals available is a photographic processing unit that converts images from negatives into a picture on a television monitor. These TV pictures can be viewed to determine whether they are clear enough to be used in court. They can be manipulated by changing the contrast or by zooming in on the driver or license plate. Also, the passenger or any other image in the picture can be blacked out or excluded from the photograph, and the resulting image can be printed instantaneously.

Feasibility of Use on the Capital Beltway

Since photo-radar use had proven feasible in several American and European cities, the study proceeded to the issue of whether photo-radar use would be technically and operationally feasible in the high-speed, high-volume environment of the Capital Beltway. A major aspect of feasibility was the accuracy of the equipment and the clarity of the photographs produced. Without documented evidence as to its accuracy, photo-radar use would not pass muster with the courts, and without a sufficient number of clear, readable photographs, too few citations would be produced to make the program worthwhile. Another major aspect of feasibility was whether the specific units could perform adequately in varying conditions. Thus, field demonstrations of each of five manufacturers of photo-radar equipment were conducted during the summer of 1990 on Interstates 64, 81, 95, 295, and 495 in Virginia and I-95 in Maryland. The equipment of each of five manufacturers was tested for a 2-week period. The demonstrations yielded the following results:

- Accuracy of recorded speeds: Unless a speed enforcement device is accurate, both the courts and the motoring public will reject it. To test the accuracy of the photo-radar equipment, test vehicles were driven through the path of the photo-radar units. The speed readings generated by the individual photo-radar units were then compared with the speed measurements produced by loop detectors embedded in the pavement. (These loop sensors are permanently installed around the state to collect speed and volume data.) The accuracy of a particular photoradar unit was expressed as the percentage of times the unit measured a vehicle's speed within +2 mph or −3 mph of the speed reading generated by the loop detector. This criterion was derived as follows: (*a*) the accuracy of the police radar currently in use in the United States is +1 mph to −2 mph; (*b*) the accuracy of the loop detector is ±1 mph; (*c*) by combining these two sources of error, the standard against which the photo-radar units were measured (i.e., +2 mph and −3 mph) was developed.

The accuracy of the photo-radar units varied, with one unit's recorded speeds falling within the required range 96 percent of the time and another's falling within the range only 84 percent of the time (see Table 2). Moreover, certain units resolved speed reading errors in favor of the driver, as do ordinary police radar units used in the United States. This fosters confidence in the speed reading since it reflects an underestimation of the driver's actual speed. Clearly, in considering which type of photo-radar equipment to use, the units that most closely resemble police radar in terms of accuracy and direction of the error are most desirable, since police radar use is so widely accepted in the United States.

- Multivehicle traffic and accuracy of equipment: Test vehicles were driven in pairs through the photo-radar beam to determine the effect that simultaneously driving two or more

TABLE 1 Capabilities of Photo-Radar Equipment

	AWA	Gatso	Multanova	TMT	Traffipax	Trafikanalys
Operations						
Stationary mode	Yes	Yes	Yes	Yes	Yes	Yes
Mobile mode	No	Yes	Yes	No	Yes	No
Nighttime	Yes	Yes	Yes	Yes	Yes	Yes
Both directions at once	No	Yes	Yes	Yes	Yes	Yes
Different speeds for cars and trucks	No	Yes	Yes	No	Yes	Yes
Options						
Computer interface	Yes	Yes	Yes	Yes	Yes	Yes
Video	No	Yes	Yes	Yes	Yes	Yes

TABLE 2 Accuracy of Photo-Radar Equipment

	AWA	Gatso	TMT	Traffipax	Trafikanalys
Percentage within +2 and −3 mph	83.7	93.8	87.2	96.3	86.7
Primary direction of error	Too high	Too high	Too low	Too low	Too low

vehicles through the radar beam had on the accuracy of speed readings. The data indicated that neither the lane in which the vehicle was driven nor the pairing of vehicles affected the accuracy of the speeds recorded. Under field conditions, the photo-radar unit could isolate the speeding vehicle and record its speed without a loss of accuracy.

- Number of usable photographs: Photographs produced by a photo-radar unit must be of sufficient clarity for two reasons: (*a*) a registered owner of a vehicle cannot be cited if the license plate of the vehicle is illegible, and (*b*) a court probably will not admit a blurred photograph as the sole evidence of a speeding violation. The numbers in this summary represent the percentage of speeding vehicles passing each unit that the unit could detect and then clearly photograph. The number of clear (i.e., usable) photographs varies with traffic volume, vehicle speed, threshold speed setting, and site selection.

When the photo-radar equipment was deployed to photograph oncoming traffic, the most efficient unit adequately detected and photographed 2.4 percent of those vehicles exceeding the speed limit and the least efficient unit adequately detected and photographed 1.7 percent (see Table 3). In terms of expected number of citations produced per hour, the least efficient unit would produce 9 citations per hour and the most efficient unit would produce 65 citations per hour, both in the oncoming mode.

Although the percentages of speeding vehicles adequately photographed appear quite low, the citation rate for the least efficient equipment still exceeds the number of citations that could be written by a police officer in 1 hr. The most efficient units produce far more citations per hour than an officer could write. Moreover, these figures do not measure the deterrent effect of photo-radar on speeding drivers. Therefore, photo-radar still might prove highly effective at speed enforcement even if it fails to detect and photograph the majority of speeding drivers.

- Effect of misalignment on accuracy: It is possible that photo-radar equipment will be operated under conditions that do not meet the exacting requirements of experimental conditions. To account for this, the researchers deliberately misaligned the photo-radar equipment up to a maximum of 8 degrees. With the exception of the AWA unit, the misalignment resulted in a maximum error of +3 mph. For the AWA equipment, a misalignment of 8 degrees caused a maximum error of +9 mph. All misaligned units overestimated vehicle speed.
- Ease of detection by radar detectors: It is reasonable to surmise that some drivers will attempt to evade photo-radar speed enforcement through the use of a radar detector. With that in mind, the researchers tested the distance at which each manufacturer's equipment was detectable. A test vehicle with the radar detector installed was driven slowly toward the equipment until it actuated the radar detector. The location of detection was marked, and the distance from the equipment measured.

Both the AWA and the Trafikanalys equipment were detected by the radar detector at 2,250 ft, and both the Gatsometer and Traffipax equipment were detected at 1,056 ft. The radar detector did not detect the TMT equipment since the radar detector used could not pick up the Ka band.

- Effect of photo-radar use on speed characteristics: To measure whether photo-radar use will reduce speeds requires full enforcement of photo-radar citations and increased motorist awareness of photo-radar use, both of which were outside the scope of the study. With this in mind, photo-radar use during the test runs produced a statistically insignificant reduction in the mean speed, which varied according to both the site and the equipment used. Further reductions can prob-

TABLE 3 Efficiency of Photo-Radar Equipment in Oncoming Traffic

	AWA	Gatso	TMT	Traffixpax	Trafikanalys
Total number of speeding vehicles passing the equipment	425	720	1,201	—	2,737
% of all speeding vehicles photographed well enough to issue a citation	2.0	1.7	2.0	—	2.4
Expected number of citations per hour	9	12	24	—	65

ably be expected if drivers are made aware of photo-radar use and are actually ticketed because of detection by a photo-radar unit.

Public Support

Even after a speed enforcement technology gains judicial acceptance, it must withstand the attacks of perhaps its most difficult critic: the motoring public. Public opinion polls in Pasadena and Paradise Valley indicate that motorists favor photo-radar use in residential areas on local roadways, but virtually all of the ticketed drivers are nonlocal. Application to an Interstate highway poses a unique set of concerns. To determine public sentiment on the issue of photo-radar implementation on the Capital Beltway, a cross section of Maryland, Virginia, and District of Columbia residents was sampled.

Approximately 60 percent of those sampled either approved or strongly approved of photo-radar use as a speed enforcement tool, and approximately 35 percent of respondents disapproved or strongly disapproved of its use (see Table 4). Roughly 5 percent of respondents had no opinion. Although less than 2 percent of respondents named photo-radar as a speed enforcement tool without its being suggested, once mentioned, 78 percent of respondents claimed to have heard of photo-radar technology.

Nondrivers and non-Beltway drivers felt more positively concerning photo-radar than did drivers or Beltway drivers. Moreover, women were more inclined to favor photo-radar use than men, and District of Columbia residents viewed it more favorably than Virginia or Maryland residents.

Generally, the findings support two assertions. First, despite certain gender-specific and geographic-specific variations in the results, those least affected by potential photo-radar use on the Beltway were the most positive concerning its use. Confirming intuition, Beltway drivers were more likely to oppose photo-radar use than the other drivers sampled. Second, the overall attitude of those sampled toward photo-radar as a speed enforcement device was positive. Even among Beltway drivers, the segment most skeptical of photo-radar use, there was a 53 percent approval rating.

TABLE 4 Public Opinion Concerning Potential Photo-Radar Use on Capital Beltway

Response	Percent of Respondents	
Strongly approve	16.7	(59.3)
Approve	42.6	
Disapprove	19.9	(35.1)
Strongly disapprove	15.2	
No opinion	5.6	

CONCLUSIONS AND RECOMMENDATIONS

It is feasible to use photo-radar technology to detect and cite speed violators on high-speed, high-volume roads. This advance in speed enforcement technology will undoubtedly encounter significant resistance by at least some segments of the motoring public. Moreover, the limits of the study itself should be noted: the study did not determine whether photo-radar use is cost-effective given the staff requirements and administrative costs of its operation. However, if photo-radar meets the requirements of the National Institute of Standards and Technology for accuracy and withstands initial legal challenges, then it should gain acceptance as an effective tool in speed enforcement. Effective photo-radar legislation could safeguard individual rights, meet constitutional requirements, and enhance the litigation of speed violations. (These conclusions are discussed in detail and supporting documentation is presented in the full report.) As part of its continuing commitment to improve safety on the highways, it is recommended that Virginia take steps to test and evaluate further the effectiveness of photo-radar in reducing speeds in traffic situations where traditional techniques for speed enforcement are impractical or unsafe.

Publication of this paper sponsored by Committee on Traffic Law Enforcement.

Legal Issues Concerning the Use of Photo-Radar

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As part of a study on the potential use of photo-radar equipment on high-speed, high-volume roads, the Virginia Transportation Research Council conducted research on the legal issues raised by the use of photo-radar technology. A historical review of speed enforcement technology was conducted, starting with the time-distance method of speed enforcement and continuing through modern photo-radar technology. The various legal issues related to the use of photo-radar devices, both in staffed and unstaffed modes, are examined. In particular, potential constitutional challenges to the use of photo-radar, the admissibility of photographs produced by photo-radar under the pictorial testimony theory and the silent witness theory, requirements for legal service, and the need for federal approval for unstaffed use of photo-radar systems are discussed. Model enabling legislation for implementing photo-radar technology is provided.

In recent years, many police agencies have been forced to operate with less staff because of reduced local funding. This puts the time of police officers at a premium. Since their other duties have remained largely the same (and in many cases have increased), officers and their supervisors must prioritize their duties and devote the majority of their time to activities that they believe most affect the public good. Thus, although speed enforcement is not altogether ignored, the time devoted to it is often limited. This frustrates local officials, since they recognize the dangers to the public caused by speeding drivers.

In some localities, enforcement officials face escalating speed problems that they cannot address by use of the usual speed enforcement techniques. As high-speed, limited access highways are widened and traffic volumes increase on these roads, it becomes extremely difficult to stop vehicles safely to issue "speeding tickets." Under such conditions, normal speed enforcement is difficult, if not impossible. In addition, roadside citation of drivers is time-consuming, and thus many violators escape detection. Since a driver's perceived risk of being cited for a speeding violation is a powerful deterrent, reduced enforcement threatens the ability to control speeds. Against this backdrop, law enforcement officials and traffic experts alike have suggested that photo-radar may provide an effective speed enforcement technique as well as a strong deterrent to speed violations.

Photo-radar is an automated speed enforcement device that uses Doppler radar to detect a vehicle that is traveling over a threshold speed. The device photographs the vehicle, its license plate, and, with certain equipment, the face of its driver. The time, date, location, travel speed, and posted speed are automatically listed on the photograph for evidentiary purposes. Moreover, the equipment can be operated with or without a police officer present. "Unstaffed" photo-radar units have operated in Europe for many years. In the United States photo-radar equipment has been successfully deployed in the "staffed" mode in Pasadena, California, and Paradise Valley, Arizona, for several years under local ordinances. Photo-radar thus far has been used only on a community basis. Suggestions to expand its use to Interstate highways in Maryland and Virginia justify an evaluation of the constitutional, legal, and evidentiary issues associated with photo-radar use.

PURPOSE AND SCOPE

The purpose of this study is to examine the constitutional, evidentiary, and legal issues associated with the use of photo-radar devices. A secondary objective is to draft sample enabling legislation for the implementation of photo-radar technology.

With this in mind, the scope of this study is necessarily limited. It does not address the cost or the benefits of photo-radar, nor does it comment on the ultimate feasibility of photo-radar outside of considering the legality of its use.

HISTORY OF PREVIOUS SPEED ENFORCEMENT AND PHOTO-RADAR TECHNOLOGY

Many people approach the use and evaluation of photo-radar as if it were a new and uniquely invasive technology. In fact, photo-radar equipment is simply the combination of several pieces of previously existing equipment—camera, radar, and electronic controls—all of which have been used either together or separately in enforcement and prosecution of offenses for many years. The validity and reliability of these older forms of speed enforcement technology had to be proved to both the police and the courts before general acceptance. Thus, it is important to consider the use of photo-radar in the context of (*a*) the history of previous speed enforcement technology and (*b*) the history of photo-radar technology.

History of Speed Enforcement Technology

In the past, the introduction of a new and innovative speed enforcement technology often generated a negative reaction.

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The public's distrust of the use of high technology by enforcement officials is often evidenced by claims that the technology is simply another attempt by "Big Brother" to invade their lives. When radar was first introduced in the 1950s, *Time Magazine* ran an article headlined "Big Brother Is Driving," the text of which characterized radar as being "as invisible as the Thought Police in Orwell's chiller [1984]" (*1*). The use of radar was also challenged as being unconstitutional (*2*). The history of speed enforcement is replete with examples of new enforcement techniques; subsequent negative public reaction and resistance; and, assuming survival through legal challenges, ultimate acceptance.

Time-Distance Method

The use of the first known method of speed enforcement dates back to 1902 in Westchester County, New York. This system was composed of three dummy tree trunks set up on the roadside at 1-mi intervals. A police officer with a stopwatch and a telephone was concealed in each trunk. As a speeding vehicle passed the first trunk, the hidden police officer telephoned the time to the second police officer, who recorded the time at which the vehicle passed him and then computed its speed for the mile. If the vehicle was exceeding the speed limit, the officer telephoned the third police officer, who proceeded to stop the vehicle by lowering a pole across the road (*3*). The tree trunk method was subject to hearsay objections in court because officers had to testify regarding the time statements of other officers, since there was no way to observe the vehicle over the entire distance (*4*).

This is an early example of the time-distance method of speed enforcement. Time-distance measurements are computed by measuring the time taken to traverse a distance of known length (*5*). Several methods of speed enforcement employ the time-distance principle. Pavement markings or mirror boxes that are observed by police officers with a stopwatch have replaced dummy tree trunks, and two-way radios between patrol cars or aircraft have replaced the telephone system, but the technique remains much the same (*6*).

The speedwatch, also referred to as the Prather speed device, was one of the first electric timers to employ the time-distance principle (*7*). This device consisted of two rubber tubes that were stretched across a street a known distance apart. The tubes were connected to two switches, which were in turn connected to a control panel containing a stopwatch, a switch, and a reset button. A police officer was positioned to observe both tubes, and when a vehicle approached, he flipped the switch to activate the first tube. On contact with the tires of the vehicle, the switch in the first tube started the stopwatch, which was stopped when the vehicle hit the second tube. The stopwatch was scaled to reflect the speed of the vehicle (*8*). The speedwatch is believed to have been accurate to within 2 mph, and the officer's testimony concerning his observation of the speeding vehicle and the accuracy of the instrument was admissible in most courts (*9*).

The most recent technique employing time-distance measurements is the visual average speed computer and recorder (VASCAR). VASCAR is a computerized system that computes the speed of a car by measuring the distance between two fixed markers and the time taken to travel it, thereby giving the observing police officer a quick, easily readable speed determination (*10*).

In 1947, only one state used a time-distance device (*11*), but by 1970, 34 states used at least one—the majority using VASCAR or aerial surveillance (*12*). Because time-distance devices have been categorized as "speed traps," their use has been prohibited in at least two states: California and Washington (*13*).

Pacing

Another widely used method of speed enforcement in the 1940s was pacing (*14*). Police officers paced a speeding vehicle by following it for a specified distance and observing the speedometer of the police vehicle to calculate the average speed of the paced vehicle over the distance. In 1947, 20 percent of the states required pacing before apprehension of a speeding driver (*15*). A large percentage of states used unmarked cars, identifiable only by decals, or motorcycles as pacing vehicles (*16*). Because pacing depends on the accuracy of the pacing vehicle's speedometer, many states adopted the use of calibrated speedometers and regulations defining the frequency with which speedometers must be calibrated (*17*).

Tachograph

The tachograph, also referred to as a tactograph or tachometer, was a speed enforcement method used by trucking companies to control the speed of truck drivers. The tachograph contained a clock with a paper dial attached to the driveshaft or transmission of the truck. The dial recorded the speed of the truck at any given time (*18*). The chart produced by this device was used to corroborate the testimony of the arresting officer (*19*); ironically, however, it was often admitted into evidence to prove the innocence of the implicated driver (*20*).

Radar

Police radar was introduced in the late 1940s and early 1950s. Although generally referred to as "radar," police radar is not technically radar. True radar has the ability to measure an object's distance, direction, and size as well as its speed, but police radar measures only speed. Police radar operates according to the scientific principle known as the Doppler effect: the frequency of sound waves (or microwaves) being emitted by or reflected from an object will vary in direct relation to the speed of the object itself. The Doppler effect is noticeable in everyday life in the rising and falling of a car horn's pitch as the car approaches and passes. Police radar transmits microwaves at a set frequency. When the microwaves are reflected from a vehicle, the frequency of the returning microwaves shifts because the vehicle is in motion. This shift in the original frequency, the Doppler shift, is measured by the radar device, which converts the signal into a measurement of the vehicle's speed.

An early hurdle encountered by police radar (hereinafter called radar) was evidentiary in nature. Before judicial notice was taken of the underlying principle involved, courts required that an expert witness testify as to radar's accuracy and reliability (*21*). The Virginia Supreme Court was among the first courts to take judicial notice of radar's underlying principle, thereby eliminating the need for expert testimony (*22*). However, testimony as to the accuracy of the particular machine used to detect the violation is still required in Virginia.

Constitutional questions have also arisen in radar cases, as they invariably do whenever a new scientific technique becomes useful in enforcement (*23*). A Virginia statute providing that radar evidence constitutes prima facie evidence of speeding was found to be constitutional under the Fourteenth Amendment of the U.S. Constitution (*24*). The defendant in the case argued that the provision was tantamount to his being presumed guilty (*25*). However, the court held that the defendant was still presumed innocent under such a standard (*26*). A Pennsylvania due process claim based on the alleged instantaneousness of the machine's determination and the potential for error was likewise denied (*27*). In denying that claim, the court noted the complete absence of cases holding the use of radar for speed measurement to be unconstitutional (*28*). Cases raising the issue of a citizen's constitutional right against self-incrimination have likewise been unsuccessful (*29*).

History of Photo-Radar Technology

Law enforcement's latest innovative technology for the enforcement of speed laws is photo-radar. Photo-radar equipment combines a camera and radar with electronic controls to detect and photograph a speeding vehicle. The unit can photograph the driver's face and the front license plate if deployed to photograph oncoming traffic, or the rear license plate if deployed to photograph receding traffic. The license number of the speeding vehicle is extracted from the picture, and a citation is sent to the registered owner of the vehicle. The radar used in photo-radar equipment operates on the same Doppler principles as the radar used by police.

Although photo-radar is a relatively new technology in the United States, it is not the first speed detection device to use a camera. In 1910, a device known as a photo speed recorder was used in Massachusetts (*30*). The photo speed recorder consisted of a camera, synchronized with a stopwatch, that took pictures of a speeding vehicle at measured time intervals. The speed of the vehicle was determined by a mathematical calculation based on the reduction in size of the vehicle in the photograph as it moved farther away from the camera. This photographic evidence was held admissible by the Supreme Judicial Court of Massachusetts, and the scientific approach was judged more reliable than eyewitness testimony because it did not rely on the "fluctuations of human agencies" (*31*).

However, in 1955, the unattended use of the photo-traffic camera (Foto-Patrol) was prohibited in New York because of the difficulty in identifying the driver of the vehicle (*32*). The Foto-Patrol device, a camera mounted on the side of the road actuated by an electronic impulse when passed by a vehicle traveling in excess of a predetermined speed, took a picture of the rear license plate only, making it impossible to identify the driver. The court was unwilling to adopt the presumption that the driver was the registered owner of the vehicle, absent any corroborating evidence, and prohibited the use of Foto-Patrol unless it was staffed by an attending officer available to stop and identify the driver on the spot (*33*).

The problem of driver identification was resolved by the Orbis III (Orbis) system introduced in the late 1960s (*34*). Orbis operated much like an advanced Prather speed device that used a camera (*35*). The contacts the vehicle ran over were 72 in. apart and connected to a computer that triggered the camera, which was set up to capture the vehicle's front license plate and the driver's face if the vehicle's speed exceeded a preset limit (*36*). When Orbis was introduced, it encountered a unique form of resistance (*37*). To avoid being recognized, people would speed by the Orbis machine wearing a Halloween mask (*38*). Orbis was abandoned for administrative reasons (*39*). However, research did not identify any cases that successfully challenged Orbis on legal grounds, and a study prepared for the U.S. Department of Transportation indicated that the device was probably constitutional (*40*).

It is uncertain whether photo-radar will be accepted by the public. Previous speed enforcement techniques usually gained acceptance if the technology proved accurate, and if they survived the initial constitutional and evidentiary challenges. However, even after a technology gains acceptance, drivers have often undertaken efforts to thwart the technology's effectiveness. One example of a popular form of resistance to speed detection technology is the use of a radar detector. Radar detectors sound a warning to the driver when they detect the microwave signal emitted by the radar unit. Drivers have also tried using other methods to avoid being caught speeding by radar (*41*). These methods included using transmitters designed to disrupt the radar signal, putting nuts and bolts in the hubcaps, painting the fan blades with aluminum paint, and attaching hanging chains to the undercarriage of the car (*42*). There is even a 160-page book entitled *Beating the Radar Rap* (*43*). Photo-radar will no doubt encounter many, if not all, of these methods of resistance. However, if photo-radar is proven to be accurate and if it is able to withstand the initial legal challenges, it should gain acceptance as an effective tool in speed enforcement.

Furthermore, there is evidence that the public may support photo-radar use in residential settings. In Pasadena, California, and Paradise Valley, Arizona, where photo-radar has been used in residential settings on local, non-Interstate roadways, a majority of respondents in public survey polls have been in favor of photo-radar use. However, one must interpret these findings in light of the fact that more than 90 percent of those cited for speeding in these two locations are nonresidents.

LEGAL ISSUES

Constitutional Issues

If there is one constant in speed enforcement, it is that drivers will contest speeding citations. Because constitutional attacks are easily fashioned to assert nearly any position, it can be expected that implementation of photo-radar in a state will generate constitutional challenges to its use. However, although constitutional attacks are easily levied, they are not necessarily successful. Current jurisprudence supports the constitutionality of photo-radar despite potential challenges to its use.

Although an attack might be leveled against photo-radar on the grounds that photographs produced by photo-radar violate the automobile operator's zone of privacy (*44*), such an assertion does not reflect the scope of the zone of privacy. The first explicit discussion of a right to privacy by the U.S. Supreme Court appeared in *Griswold v. Connecticut* (*45*), in which the appellants challenged a Connecticut statute prohibiting the distribution of birth control information to married persons (*46*). The court held that the Connecticut statute was unconstitutional, concluding that the marital relationship was such that it belonged within a class of fundamental rights deserving of special protection and that the Connecticut statute unnecessarily intruded into the relationship (*47*).

But the zone of privacy is narrowly construed. The rights falling under the zone of privacy are "limited to those which are 'fundamental' or 'implicit in the concept of ordered liberty' " (*48*). The activities found by the Supreme Court to fall within the zone of privacy include "matters relating to marriage, procreation, contraception, family relationships, and child rearing and education." (*49*). Placing a right within the zone of privacy limits the state's regulatory power over the activity (*50*). The operation of an automobile simply does not fall within the category of fundamental rights protected by the zone of privacy. To the contrary, the Supreme Court considers a person's expectation of privacy in an automobile to be quite limited, and automobile operation is properly subject to significant state regulation (*51*).

Another possible attack against photo-radar could be made under the Fourth Amendment right to be free from unreasonable searches (*52*) on the grounds that photo-radar photographs constitute a Fourth Amendment search. Therefore, photo-radar use is subject to the Fourth Amendment's probable cause and warrant requirements. Under the Fourth Amendment, a person has a constitutional right to freedom from unreasonable search and seizure in circumstances where the person has a reasonable expectation of privacy (*53*). This constitutional right is protected through the requirement that a police officer have probable cause and a warrant in order to engage in certain types of searches (*54*).

Unless a person exhibits a reasonable expectation of privacy under the circumstances, the Fourth Amendment warrant and probable cause requirements are not triggered (*55*). However, a person has a lowered expectation of privacy in an automobile (*56*). Moreover, "what a person knowingly exposes to the public" receives no "Fourth Amendment protection" (*57*). For this reason, in *United States v. Knotts*, the Supreme Court upheld the warrantless placement by law enforcement officers of a beeper in an automobile to monitor the vehicle's movements (*58*). According to the Supreme Court, a person traveling in an automobile on public roads has no reasonable expectation of privacy in his or her movements, since this information is knowingly exposed to all who care to look (*59*). Likewise, photo-radar merely photographs that which a person knowingly exposes to the public while driving—the person's likeness. Because of this, the use of photo-radar violates no reasonable expectation of privacy and, therefore, is not subject to the Fourth Amendment warrant and probable cause requirements.

A further claim that might be raised against photo-radar is that its use chills the freedom of association found by the Supreme Court to be implied by the First Amendment (*60*). Such a claim asserts that both drivers and passengers might avoid traveling in vehicles with individuals with whom they would normally associate to avoid being officially observed and photographed by photo-radar (*61*). This argument misconstrues the scope of associational rights. The Supreme Court has delineated two types of associational rights: (*a*) freedom of expressive association and (*b*) freedom of intimate association (*62*). The freedom of expressive association protects organization within groups for the exercise of First Amendment rights, such as freedom of speech and religion (*63*). The freedom of intimate association is an outgrowth of the privacy doctrine and protects an individual's right to engage in intimate relationships without threat from excessive governmental regulation (*64*).

Speed enforcement through photo-radar technology does not compromise freedom of expressive association for two reasons. First, a claim that photo-radar use might prevent certain individuals from traveling with persons with whom they would normally associate will not support a claim for infringement of freedom of expressive association. A showing "of specific present objective harm or a threat of specific future harm" to associational rights and First Amendment rights is necessary to support a freedom of expressive association claim when government regulations will only indirectly affect the exercise of First Amendment rights (*65*). In *Laird v. Tatum* (*66*) and *Donohoe v. Duling* (*67*), the activities of the plaintiffs' lawful political groups were under surveillance. The *Laird* plaintiffs argued that surveillance by U.S. Army observers of the activities of the political groups had a chilling effect on their First Amendment right to free speech and freedom of association (*68*). The plaintiffs in *Donohoe* claimed that the taking of pictures by uniformed police officers of persons involved in demonstrations violated the demonstrators' First Amendment rights (*69*). The Supreme Court in *Laird* held that a claim of a hypothetical chilling effect on First Amendment and associational rights would not support a freedom of expressive association claim if the government regulation did not directly prohibit First Amendment activity (*70*). Thus, the *Laird* and *Donohoe* courts held that, where government activity prevents exercise of First Amendment rights indirectly, a freedom of expressive association claim requires a specific showing of an objective present harm or threatened future harm (*71*).

Second, the freedom of expressive association claim against photo-radar is far weaker than the claims presented in *Laird* and *Donohoe* since photo-radar speed enforcement is not solely directed at groups organized for the purpose of exercising First Amendment rights. Freedom of expressive association protects association only for the purpose of exercising First Amendment rights (*72*). Successful freedom of association claims involve government regulations targeting the activities of particular groups organized specifically to exercise First Amendment rights (*73*). The only group targeted by photo-radar would be speeding drivers, who certainly do not represent an organized group, much less a group organized for First Amendment purposes.

Moreover, photo-radar use will not provide a basis for a freedom of intimate association claim. Although the boundaries of intimate association remain largely undefined, as an outgrowth of the zone of privacy, it has been used to strike down regulations that interfere with certain marital and familial relationships (*74*). Successful freedom of intimate association claims involve statutes that directly interfere with marital and familial relationships (*75*). The connection between photo-radar use and association through intimate relationships is attenuated at best. Photo-radar clearly does not prevent individuals from engaging in intimate relationships with family members or any other person for that matter and, therefore, does not implicate the freedom of intimate association.

An equal protection claim based on the fact that not all speeders would be detected by photo-radar and cited for speeding would also most likely fail (*76*). To launch a successful equal protection claim, the plaintiff must prove that the standard used to select the claimant for enforcement "was deliberately based on an unjustifiable criterion such as race, religion, or other arbitrary classification" (*77*). The inability to prosecute all violators will not provide the basis for an equal protection claim (*78*). Because a photo-radar unit requires 1 sec to reset itself after photographing a violator, not all speeding drivers passing through the photo-radar field would be detected. Thus, not all those violating the speed laws receive the same treatment. Since the determination of who is missed by photo-radar and who is caught is based on the technical abilities of the system and not on an intentional decision to discriminate on the basis of a suspect classification, an equal protection challenge to the use of photo-radar would almost certainly fail.

Finally, because a citation for a speeding violation detected by photo-radar must pass through a development process and is issued through certified mail, there is a delay between the time of the violation and the issuance of a citation that could undercut efforts by a violator to prepare a legal defense. For this reason, a ticketed driver could assert that photo-radar use constitutes a denial of due process of law. Currently, the cities of Paradise Valley, Arizona, and Pasadena, California, which use photo-radar, have circumvented due process claims by issuing citations within a given time period following the offense and by deploying signs providing considerable warning of approaching photo-radar units. Still, photo-radar is subject to a due process claim on the grounds that the element of delay hampers the ability to gather witnesses and evidence and thus to prepare a proper defense.

However, the delay involved in citing an alleged violator using the photo-radar process is relatively short, reducing the possibility that a defendant will lose access to witnesses or evidence. Access to evidence with photo-radar may, in fact, be better than with a conventional stop since photo-radar creates a photographic record of the scene where the speeding violation occurred. Further, in *United States v. Delario* (*79*) the defendant argued that a preindictment delay of more than 1 year constituted a denial of due process. The court found that the argument lacked merit and held that the defendant would have to show that the delay was a deliberate attempt by the government to gain a tactical advantage and had resulted in actual and substantial prejudice (*80*). Because the delay involved in issuing photo-radar citations cannot reasonably be viewed as an attempt by the government to gain a tactical advantage, case law suggests that a due process claim against photo-radar is also likely to fail.

If constitutional attacks against photo-radar are unsuccessful, a ticketed driver might pursue civil liability against the state under the common law right of privacy. The common law right of privacy is a tort action created by state courts permitting recovery of damages for an invasion of privacy as defined by state law (*81*). A state law action for invasion of privacy might be brought against the use of photo-radar on the basis that the unauthorized taking of a person's photograph constitutes an invasion of privacy (*82*). A common law right of privacy claim against a local government for the use of photo-radar is likely to fail for several reasons.

First, courts have repeatedly held that an individual's privacy must yield to the reasonable exercise of a state's police power (*83*). Included within the state's police power is the authority to photograph persons charged with a crime (*84*). Thus, in *Downs v. Swann*, the Maryland Court of Appeals rejected a claim for invasion of privacy against the Baltimore Police Department on the grounds that photographing and fingerprinting a suspect charged with a crime did not violate the suspect's right of privacy (*85*). As long as the police department neither published the pictures nor gave the pictures of suspects not yet convicted to a rogue's gallery, the police department was not subject to the common law right of privacy (*86*). Second, state courts have indicated that there is no invasion of privacy under the common law right of privacy if the photographing of an individual by a law enforcement agency does not violate a reasonable expectation of privacy under the Fourth Amendment (*87*). These opinions suggest that a law enforcement agency may photograph whatever a person knowingly exposes to the public without violating the common law right of privacy.

Finally, certain states do not recognize the common law right of privacy (*88*). The law of such states does not countenance a damages action against a law enforcement agency for the use of photo-radar photographs in speed enforcement. Thus, in those states not recognizing a common law right of privacy, and even in those states that do, no tort action should lie against the use of photo-radar.

Evidentiary Issues

Photo-radar devices detect speeders by radar and then photograph the front or rear license plate of the vehicle and, in most cases, the driver. In Pasadena, California, and Paradise Valley, Arizona, police officers are always present when the devices are in operation. If the registered owner of the vehicle challenges the citation, the attending officer testifies in the court proceeding as to the accuracy of the background scene depicted in the photograph and compares the likeness of the driver in the photograph to the registered owner. No appellate challenges regarding evidentiary issues have occurred in either locality.

A photograph is usually admitted into evidence under the pictorial testimony theory. Under this theory, photographic evidence is admissible only when a witness has testified that it is a correct and accurate representation of relevant facts personally observed by the witness (*89*). However, it is not necessary that the witness be the actual photographer (*90*). The witness is required to know only about "the facts represented or the scene or objects photographed, and once this knowledge is shown he can say whether the photograph correctly and accurately portrays these facts" (*91*). Prosecutors in Pasadena and Paradise Valley have proceeded under the pictorial testimony theory when introducing photo-radar photographs into evidence. Because their photo-radar devices are attended by police officers, the officers can testify in court that the photographs are accurate representations.

For any proposed system for use on the Beltway, it is likely that the device will be attended by a police officer. If unattended use is anticipated, a different theory must be used to admit the photographs into evidence. This newer theory of admission is referred to as the "silent witness" theory (*92*). Under this doctrine, photographs constitute " 'substantive evidence' in the sense that photographic evidence alone can support a finding by the trier [of fact]" (*93*). Thus, under the silent witness doctrine, "photographic evidence may draw its verification, not from any witness who has actually viewed the scene portrayed on the film, but from the reliability of the process by which the representation was produced" (*94*). The silent witness theory, however, is not accepted in all jurisdictions (*95*).

In those jurisdictions that accept the silent witness theory, it will be necessary to address potential reliability problems associated with the use of the photo-radar system. The unstaffed use of the photo-radar system poses a reliability problem since tampering with the system would be possible. However, this difficulty could be remedied by producing evidence that tampering does not affect the accuracy of the system or that tampering did not occur in the situation in question.

One other reliability issue may arise in connection with the use of the photo-radar system. In some instances, more than one vehicle may be shown in the same photograph, thereby creating difficulty in determining which of the drivers was speeding. Charles Ollinger, Town Attorney for Paradise Valley, explained that this difficulty is easily resolved. Older photo-radar cameras have a 29-degree field angle; the newer models have a 22-degree field angle. The radar equipment has a 5-degree field angle. On the photograph taken by the photo-radar device, the portion of the photograph containing the radar field can be distinguished. Thus, the car in that portion of the photograph is the speeding vehicle detected by the radar system. Some photo-radar systems use a template, which is placed over the picture, to identify the speeding vehicle when there is more than one vehicle in a photograph.

Requirements for Legal Service

Some of the photo-radar systems under consideration use a procedure by which the company providing the photo-radar service mails the speeding citation to the residence of the alleged offender.

Legislative action would assist in the implementation of photo-radar as a viable speed detection system. Specifically, the adoption of statutes that provide for service of traffic citations by mail would facilitate implementation, as would codification of the silent witness theory of admissibility for photo-radar photographs.

Federal Approval for Unattended Use

It is presently anticipated that the photo-radar units will be attended by police officers, at least initially. However, the photo-radar units are capable of operating unattended. Radar equipment operates at frequencies that fall within the area the Federal Communications Commission (FCC) has designated as Radio Location Service. Radio Location Service refers to the band of radio frequencies that are used to determine speed, direction, distance, or position for purposes other than navigation (*96*). During a telephone conversation on April 1, 1991, Eugene Thompson of the FCC's Rules and Regulations Bureau stated that FCC policy presently prohibits the use of unattended radar equipment when the return radar signal is not being used for some purpose. The example cited was the practice of emitting a constant radar signal for the purpose of triggering drivers' radar detectors. Mr. Thompson indicated that the FCC's policy on this use of unattended radar is documented in public notices dating back to 1978. Mr. Thompson stated, however, that the FCC's policy prohibiting unattended radar would not apply to the use of photo-radar since a photo-radar unit uses the return radar signal to trigger the unit's camera. Mr. Thompson also stated that the state police, as a public safety agency, would not need to receive a waiver or special permission from the FCC to use the photo-radar units in the unattended mode.

MODEL PHOTO-RADAR STATUTE

The enabling legislation for photo-radar was drafted with two important objectives in mind. First, the legislation allowing photo-radar use should be limited until its use gains acceptance by the courts and the motoring public. Second, the legislation must address the myriad constitutional and evidentiary issues posed by the introduction of photo-radar. By embodying these principles in the enabling legislation, a statute is produced that not only ensures fair application of the technology but also provides guidance for law enforcement officers and state courts in interpreting the law. As an example, the model legislation given in the Appendix was drafted for Maryland, but the principles involved would apply to many other states as well.

Proposed Maryland Code Section 26-201(n)(i) restricts the use of photo-radar to Capital Beltway speed enforcement by the State Police and limits its duration with a sunset clause that expires in 1994. Limiting the scope, duration, and control of photo-radar increases its attractiveness to a legislature by emphasizing that the legislation is intended to address the specific problem created by speeding drivers.

Sections 26-201(h)(3) and (4) of the Maryland legislation adopts guidelines for admissibility of photo-radar evidence. The statutory requirement that the photograph be of sufficient quality to identify the driver will aid implementation of the statute in two ways. First, it will signal to the legislature that the purpose of the statute is to target those drivers who are speeding on the Beltway, not to impose strict liability on the registered owners and lessees of photographed vehicles. Second, by providing a guideline for law enforcement officers as to the quality of picture required for admission of photo-radar evidence, the statute will minimize the charging of individuals for violations a court might dismiss. Requiring the police officer who actuated the photo-radar equipment to testify about the camera placement and accuracy of the scene depicted satisfies the rule of evidence that someone must testify that the photograph is an accurate representation of the scene portrayed. However, if unstaffed photo-radar is used, the legislature should codify the silent witness theory.

Sections 26-201(h)(5) and (6) accomplish the same objective as a rebuttable presumption that the registered owner or lessee is the driver of the photographed vehicle while avoiding the ruling under *Sandstrom v. Montana* (*97*) that use of a rebuttable presumption in an element of a criminal offense is unconstitutional since it shifts the burden of proof from the state to the defendant. Section (5) under the model statute imposes liability on the registered owner or lessee of the photographed vehicle for violation of the statute, but Section (6) provides an affirmative defense to a registered owner or lessee who identifies the driver at the time of the violation.

The provisions under Section 26-201(h)(7) in the model statute create a mechanism for targeting the actual driver of the photographed vehicle once the registered owner or lessee identifies the driver. This will also aid passage by indicating to the legislature that the only individuals who will be charged with violation of this statute are speeding drivers and recalcitrant owners and lessees. Section 26-201(h) will also aid the passage of this legislation by providing lesser sanctions for those violators detected by photo-radar as compared with those sanctions imposed for speed violations detected by police officers. This emphasizes that the goal of this legislation is speed reduction, not the creation of technologically advanced speed traps.

Section 26-201(h)(8)(I) outlines the procedures for citation of registered owners, lessees, and drivers. In providing the additional procedures for the citation of identified drivers, this section enhances the process for ticketing speeding drivers, furthering the objective of speed reduction. More important, this section's provision that citations be sent by certified mail preempts a potential constitutional challenge by ensuring that the alleged violator is given adequate notice of any violation.

As written, this legislation presents a coherent policy for the implementation of photo-radar equipment. It confronts the variety of legal issues arising from the introduction of such an innovative technology. Furthermore, it does so by providing significant constitutional and evidentiary protection to alleged violators as well as guidance to the legal system on the adjudication of violations detected by photo-radar.

APPENDIX

MODEL STATUTE

A Bill Entitled
AN ACT concerning
Vehicle Laws—Photo-Radar Devices—
Speeding Citations

For the purpose of requiring a police officer who, based on evidence obtained by means of a photo-radar device, has probable cause to believe that the driver of a vehicle has exceeded the posted speed limit, to mail a citation to the registered owner of the vehicle and to keep a copy of the citation; charging the registered owner, lessee, or identified driver of the vehicle with violation of this Act; providing that certain requirements relating to the signing of a citation by the person charged do not apply to a citation issued under this Act; defining a certain term; making stylistic changes; and generally relating to the issuance of citations for speeding based on evidence obtained by photo-radar devices.

By repealing and reenacting, without amendments,
Article—Transportation
Section 21-807
Annotated Code of Maryland
(1987 Replacement Volume and 1989 Supplement)

By repealing and reenacting, with amendments,
Article—Transportation
Section 26-201 and 26-203
Annotated Code of Maryland
(1987 Replacement Volume and 1989 Supplement)

SECTION 1. BE IT ENACTED BY THE GENERAL ASSEMBLY OF MARYLAND, That the Laws of Maryland read as follows:

Article—Transportation

21-807.

In each charge of a violation of any speed regulation under the Maryland Vehicle Law, the charging document shall specify:

(1) The speed at which the defendant is alleged to have driven;

(2) If the charge is for exceeding a maximum lawful speed, the maximum speed limit applicable at the location; and

(3) If the charge is for driving below a minimum lawful speed, the minimum speed limit applicable at the location.

26-201.

(a) A police officer may charge a person with a violation of any of the following, if the officer has probable cause to believe that the person has committed or is committing the violation:

(1) The Maryland Vehicle Law, including any rule or regulation adopted under any of its provisions;
(2) A traffic law or ordinance of any local authority;
(3) Title 9, Subtitle 2 of the Tax—General Article;
(4) Title 9, Subtitle 3 of the Tax—General Article; or
(5) Article 56, Sect. 148 of the Code.

(b) A police officer who charges a person under this section, except for a violation of Title 21, Subtitle 8 of this article detected by a "photo-radar device," shall issue a written traffic citation to the person charged. A written traffic citation should be issued by the police officer or authorized representative of any other state agency or contractor designated by the State for any violation of Title 21, Subtitle 8 of this article detected by a "photo-radar device" as described in this section.

(c) A traffic citation issued to a person under this section shall contain:

(1) A notice to appear in court;
(2) The name and address of the person;
(3) The number of the person's license to drive, if applicable;

(4) The State registration number of the vehicle, if applicable;

(5) The violation charged;

(6) Unless otherwise to be determined by the court, the time when and place where the person is required to appear in court;

(7) A statement acknowledging receipt of the citation, to be signed by the person;

(8) On the side of the citation to be signed by the person, a clear and conspicuous statement that:

(i) The signing of the citation by the person does not constitute an admission of guilt; and

(ii) The failure to sign may subject the person to arrest; and

(9) Any other necessary information.

(d) Unless the person charged demands an earlier hearing, a time specified in the notice to appear shall be at least 5 days after the alleged violation.

(e) A place specified in the notice to appear shall be before a judge of the District Court, as specified in Sect. 26-401 of this title.

(f) An officer who discovers a vehicle stopped, standing, or parked in violation of Sect. 21-1003 of this article shall:

(1) Deliver a citation to the driver or, if the vehicle is unattended, attach a citation to the vehicle in a conspicuous place; and

(2) Keep a copy of the citation, bearing [his] the officer's certification under penalty of perjury that the facts stated in the citation are true.

(g)(1) A law enforcement officer who discovers a motor vehicle parked in violation of Sect. 13-402 of this article shall:

(i) Deliver a citation to the driver or, if the motor vehicle is unattended, attach a citation to the motor vehicle in a conspicuous place; and

(ii) Keep a copy of the citation, bearing the law enforcement officer's certification under penalty of perjury that the facts stated in the citation are true.

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The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the sponsoring agencies.

Publication of this paper sponsored by Committee on Motor Vehicle and Traffic Law.

Spectral Analysis of Vehicle Speed Characteristics

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Characteristics of individual vehicle speed are important when evaluating the safety of the traveling public, traffic level of service, and driver behavior. Traditional research is based on analysis in the time or space domain, and its scope is sometimes limited because of lack of methodology or limitations of those domains. Results of a study using a maximum entropy spectral analysis approach to evaluate driver behavior related to driving speed under heavy and light traffic conditions, rainy and dry weather conditions, ramp impacts, and different driver operating characteristics are presented. Three test sites were chosen in the Albany area. Speed of a testing vehicle between two fixed points was recorded and transferred to spectral density functions. Impacts of traffic conditions, weather conditions, vehicles entering from ramps, and driver behavior can be identified from these spectral density characteristics. Basic concepts of maximum entropy spectral analysis and results of the field experiments are presented.

In the 1985 *Highway Capacity Manual* (*1*), traffic speed, volume, and density are defined as basic traffic flow measures. Among these variables, characteristics of individual vehicle speed are important factors when evaluating safety of the traveling public, traffic level of service, and driver behavior. In the past, research has evaluated characteristics of vehicle speed and their impacts on environments, as well as impacts of environments on vehicle speed. For example, relationships among traffic flow, speed, and concentration and statistical distributions of traffic characteristics have been addressed and revised since traffic flow theory began developing in the 1930s with applications of probability theory (*2–7*). Other research regarding speed impacts on environments and environmental impacts on speed cover many topics, such as freeway speed profiles and fuel consumption relationships (*8*), measure of level of service (*2,9*), free-flow speed prediction (*10*), enforcement strategy effects on traffic speeds (*11,12*), and freeway weaving impacts (*13,14*). The results have produced good guidelines, references, and specifications for traffic control, development of traffic flow theory, highway construction, design, maintenance, and other highway operations.

However, traditional research is based on analysis in the time or space domain, and its scope is sometimes limited because of lack of methodology or limitations of those domains. The Engineering Research and Development Bureau of the New York State Department of Transportation recently completed a research study to evaluate traffic flow in the frequency domain rather than the time or space domain. Spectral analysis techniques have been used in transportation engineering for many years in such areas as pavement surface roughness (*15*), traffic flow prediction (*16*), and pavement transverse-crack spacing evaluation (*17*). The study reported here evaluated driver behavior related to driving speed as affected by heavy and light traffic, rainy and dry weather, and entering traffic from ramps using a maximum entropy spectral analysis (MESA) approach. The basic idea of MESA is to transfer individual vehicle speed recorded in the time or space domain to spectral density in the frequency domain by the maximum entropy spectral estimate method (*18*). Impacts of traffic conditions, weather conditions, entering vehicles from ramps, and driver behavior can be identified from spectral density characteristics. During this study, field experiments focused on freeway traffic because traffic lights on local roads would stop traffic, which was not desired in this study. I-87, I-90, and I-787 were chosen as test sites.

MESA CONCEPT

Discrete Spectral Transformation

Vehicle speed data sampled at time interval T can be abstracted as a discrete sequence, called the discrete speed sequence or

$$\{V_i\} = \{V_1, V_2, \ldots, V_N\} \tag{1}$$

where V_i = ith vehicle speed data sampled at time interval T (sec). Figure 1 shows a typical discrete speed sequence collected from I-87 during a non-rush-hour period. Consider the inverse discrete Fourier transformation of the discrete speed sequence defined by Oppenheim (*19*):

$$V_i = \frac{1}{N}\sum_{k=0}^{N-1} H_k e^{jik2\pi/N} \qquad (i = 1, 2, \ldots, N) \tag{2}$$

where

N = length of the sequence (number of data points in the sequence),
V_i = ith vehicle speed data,
H_k = weights ($k = 0, 1, 2, \ldots, N - 1$), and
$j = (-1)^{1/2}$

Equation 2 states that V_i can be considered a weighted summation of sine function $e^{jik2\pi/N}$. If a new variable ω_k is defined by

$$\omega_k = k2\pi/N \qquad (k = 0, 1, 2, \ldots, N - 1)$$

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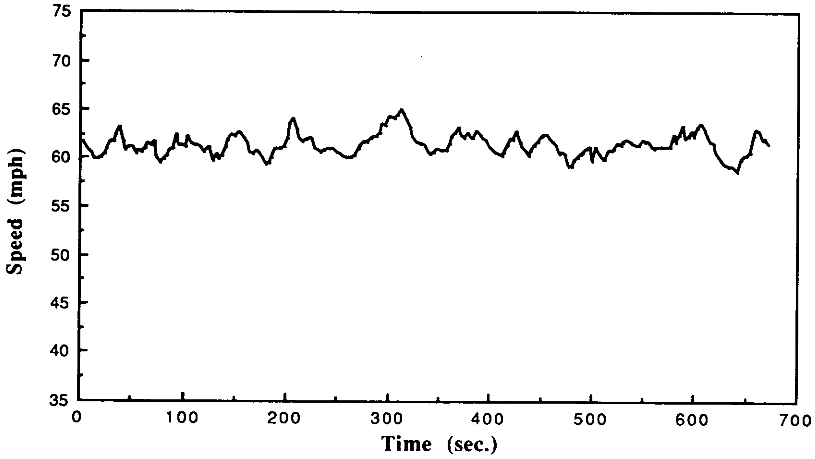

FIGURE 1 Speed sequence collected from Test Site 1 (light traffic, dry, all lanes).

then

$$V_i = \frac{1}{N}\sum_{k=0}^{N-1} H_k e^{ji\omega_k} \qquad (i = 1, 2, \ldots, N) \tag{3}$$

and

$$e^{ji\omega_k} = \sin \omega_k i + j \cos \omega_k i$$

Usually, the variable ω_k is called frequency and is within the range $[0, 2\pi(N - 1)/N]$. From Equation 2, it is known that the larger the H_k, the more sine function components with frequency ω_k the discrete speed sequence $\{V_i\}$ contains. Mathematically, it can be proved that

$$H_k = H(\omega_k) = \sum_{i=-\infty}^{+\infty} V_i e^{-ji\omega_k}$$

$$[\omega_k = 0, 2\pi/N, 4\pi/N, \ldots, 2\pi(N - 1)/N] \tag{4}$$

In other words, $H(\omega_k)$ is the discrete Fourier transformation of $\{V_i\}$ and the function of frequency ω_k. Equation 4 implies that the discrete speed sequence $\{V_i\}$ in the space domain can be transferred into the frequency domain sequence $\{H(\omega_k)\}$, and characteristics of sequence $\{V_i\}$ can be analyzed in the frequency domain—that is, knowing $H(\omega_k)$, one can analyze the characteristics of $\{V_i\}$. Since $H(\omega_k)$ is an imaginary sequence, a real function is defined by

$$S(\omega_k) = |H(\omega_k)|^2 \tag{5}$$

where $S(\omega_k)$ is called the spectral density function of sequence $\{V_i\}$. To calculate $H(\omega_k)$ from Equation 4, the summation should be from $-\infty$ to $+\infty$. In practical engineering cases, sequence length N is finite because one cannot collect infinite sequences of data. The spectral density function $S(\omega_k)$ thus should be estimated from $\{V_i\}$ by some estimation model, instead of using Equation 4.

Simple Description of Maximum Entropy Spectral Estimation

In the area of spectral function estimation, several mathematical methods are available, such as fast Fourier transformation (FFT) (*19*), maximum likelihood spectral estimation (*18*), and maximum entropy spectral estimation (MESE) (*18*). The MESE method is one of the best.

The MESE method was introduced by Burg in 1968 (*20*). Like maximum likelihood spectral estimation, MESE is a kind of estimator of parameter estimation. Consider a discrete sequence $\{V_i\}$ with sequence length N and sample interval T. If the sequence is a stationary, zero mean, approximately normally distributed, and band-limited stochastic process, then entropy of the sequence is defined as

$$H = \frac{1}{2}\ln(2B) + \frac{1}{4B}\int_{-B}^{B} \ln [S(\omega)]d\omega \tag{6}$$

where B is band width of the sequence and $S(\omega)$ is the spectral density function of the sequence, or

$$S(\omega) = T \sum_{m=-\infty}^{+\infty} R(m)e^{-jmT\omega} \tag{7}$$

In Equation 7, $R(m)$ is defined as the autocorrelation function of sequence $\{V_i\}$

$$R(m) = E\{V_i V_{i+m}\} \tag{8}$$

Combining Equations 6 and 7, entropy is obtained by

$$H = \frac{1}{2}\ln(2B) + \frac{1}{4B}\int_{-B}^{B} \ln [T \sum_{m=-\infty}^{+\infty} R(m)e^{-jmT\omega}]d\omega \tag{9}$$

Suppose the values of autocorrelation $R(m)$ are given for $m = 0, 1, 2, \ldots, M$. Then the corresponding extension of the autocorrelation function is defined by the convolution sum

$$R(m) = -\sum_{k=1}^{M} R(m - k)a_k \qquad (m > M) \tag{10}$$

or, equivalently,

$$\sum_{k=0}^{M} R(m - k)\, a_k = 0 \qquad (a_0 = 1, m > M)$$

The method that Burg introduced maximizes entropy H with respect to $R(m)$ ($|m| > M$) with restrained condition Equation 10, so that parameters $a_1, a_2, \ldots, a_M$ can be obtained. Mathematically, this can be expressed as

$$\left.\begin{aligned} &\frac{\partial H}{\partial R(m)} = 0 \qquad (|m| > M) \\ &\sum_{k=0}^{M} R(m - k)\, a_k = 0 \end{aligned}\right\} \tag{11}$$

It can be proved that with the conditions in Equation 11, sequence $\{V_i\}$ can be related by the following autoregression model, called AR(M) model:

$$V_i = -a_1V_{i-1} - a_2V_{i-2} - \cdots - a_MV_{i-M} + e_i \tag{12}$$

where M is the order of the AR(M) model and $\{e_i\}$ is an approximately normally distributed disturbance with zero mean value. The estimate of the parameters $(a_1, a_2, \ldots, a_M)$ can be obtained by the Yule-Welker equation

$$\mathbf{R} \cdot \mathbf{A} = \mathbf{P} \tag{13}$$

where $\mathbf{R}$ is the autocorrelation matrix of sequence $\{V_i\}$. $\mathbf{R}$ is called the Toeplitz matrix:

$$\mathbf{R} = \begin{bmatrix} R(0) & R(-1) & \ldots & R(1 - M) & R(-M) \\ R(1) & R(0) & \ldots & R(2 - M) & R(1 - M) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ R(M - 1) & R(M - 2 & \ldots & R(0) & R(-1) \\ R(M) & R(M - 1) & \ldots & R(1) & R(0) \end{bmatrix}$$

and

$$\mathbf{A} = \begin{bmatrix} 1 \\ a_1 \\ a_2 \\ \cdot \\ \cdot \\ \cdot \\ a_{M-1} \\ a_M \end{bmatrix} \qquad \mathbf{P} = \begin{bmatrix} P_M \\ 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \\ 0 \end{bmatrix}$$

where $P_M = E\{(e_i)^2\}$.

Finally, with all parameters estimated by the MESE algorithm, the maximum entropy spectral density function can be expressed by

$$S(\omega) = \frac{P_MT}{\left|1 + \sum_{m=1}^{M} a_me^{-jmT\omega}\right|^2} \tag{14}$$

MESA of Vehicle Speed Characteristics

From this discussion, it can be understood that the spectral density function $S(\omega_k)$ represents the frequency density distribution characteristics of the discrete speed sequence $\{V_i\}$. The basic idea is that if the discrete speed sequence $\{V_i\}$ changes smoothly, or the driver controls his vehicle in a steady manner, then $S(\omega_k)$ contains relatively numerous low-frequency components. This means that the magnitude of $S(\omega_k)$ in the high-frequency region is fairly low. On the other hand, if the discrete speed sequence changes randomly, or the driver changes his speed abruptly, then $S(\omega_k)$ contains relatively numerous high-frequency components, and the magnitude of $S(\omega_k)$ in the high-frequency region thus is relatively higher.

Conceptually, the spectral density function in the low-frequency region represents contour characteristics or macroscopic characteristics of a speed curve in a long period, but the spectral density function in the high-frequency region represents detail changes or microscopic characteristics of the speed curve in a short period. Since frequency of speed change is limited, spectral density characteristics should be band-limited. Figure 2 shows the spectral density function of the speed curve presented in Figure 1. From this graph, it is known that spectral density function is band-limited, and low-frequency components dominate the whole spectral density function. In fact, the spectral density function shown in Figure 2 is a typical model of speed spectral density characteristics.

MESA EXPERIMENTS

Field Test Considerations

Since this study's objective was to analyze driver behavior while moving, stops caused by traffic lights, accidents, or congestion were not considered. Thus only freeways were chosen as field test sites.

The process of sampling field data is relatively simple: the testing vehicle was driven from Site A to Site B and its speed was sampled at 3-sec intervals by an instrument called the Fluke Meter. Then recorded data including speed, traffic condition, test site identification, weather condition, lane change, driver's name, date, and other information were sent to a laboratory for data reduction and analysis.

Basic field test requirements were as follows:

1. The test site should be long enough so the basic dynamic process of changing speed can be recorded. In this study, the length was 10 mi.
2. To find the difference between spectral density characteristics under heavy and light traffic flow conditions, test sites should have heavy flow during rush-hour and light flow during non-rush-hour periods.
3. A few ramps should be included because ramp impacts were to be considered.

By combining these requirements, three test sites in the Albany area were chosen: I-87 between Exits 2 and 9 (southbound), I-90 between Exits 5 and 10 (eastbound), and I-787 between Route 9W and Tibbets Ave. (southbound).

During testing, driver behavior should be as objective as possible—speed control characteristics should change ac-

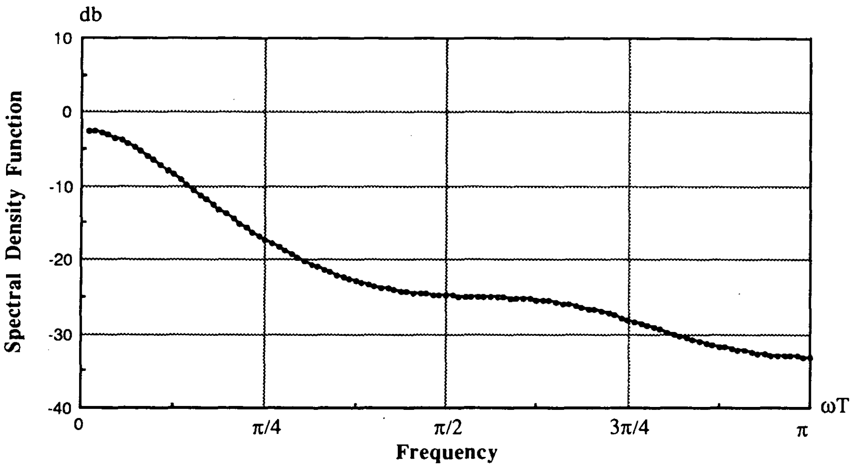

FIGURE 2 Spectral density function of speed sequence (Test Site 1, light traffic, dry, all lanes).

cording to traffic conditions, ignoring the fact that the driver is in a test situation. Figure 3 shows the field test factorial. "Right lane" means the testing vehicle always stays in the right lane (to compare ramp impacts), and "all lanes" means the driver can change lanes depending on traffic conditions. In an "all lanes" case, the impact of the ramp is less than that in "right lane."

Spectral Density Characteristics of Driver Behavior Under Varied Traffic Conditions

Heavy and light traffic conditions are two extremely different cases, in which a driver may control vehicle speed differently. Generally, when traffic is light, vehicle speed is more stable than in heavy traffic conditions. However, this difference may not be easy to identify in the time or space domains. Figures 4, 5, and 6 show speed data collected from Sites 1, 2, and 3, respectively, representing light traffic during non-rush-hour periods and heavy traffic during rush hours. Spectral density characteristics of these speed data are presented in Figures 7, 8, and 9 [vertical scale: $20\log\{S(\omega_k)\}$], from which it can be seen that these characteristics differ significantly under heavy and light traffic volumes, although these differences cannot be easily identified from Figures 4, 5, and 6. Magnitude of the spectral density function under heavy traffic is much greater than under light traffic, which means (as stated earlier) that the driver may change speed abruptly because of heavy traffic ahead of the vehicle. Statistically, the magnitude of the spectral density function resulting from heavy traffic is higher than that from light traffic. Figure 10 shows speed curves collected from Site 1 under very heavy traffic. Figure 11 shows spectral density functions resulting from speed data shown in Figure 1 representing light traffic, from Figure 4 representing heavy traffic, and from Figure 10 representing very heavy traffic. It is known that the heavier the traffic, the higher is the magnitude of the spectral density function.

		Rainy		Dry	
		Heavy Traffic	Light Traffic	Heavy Traffic	Light Traffic
Driver A	Right Lane				
	All Lanes				
Driver B	Right Lane				
	All Lanes				

FIGURE 3 Factorial for field experiments.

Weather Condition Impact on Vehicle Speed

In this study, weather condition is described as rainy or dry, and results are based on non-rush-hour traffic flow. Since no heavy rain occurred during testing, heavy rain is not discussed here. A major concern was whether rain had significant impact on individual vehicle speed by spectral analysis. The literature indicates that a wet pavement surface has less skid resistance, which affects driving safety characteristics. But it should be known whether a wet pavement surface significantly affects driver behavior in terms of speed. In this study, a few tests were conducted at the three sites to study rainy weather impact. It would be expected that during rain, a driver might keep cautiously adjusting his speed to find a desired level that he considers safe. He might not accelerate or decelerate quickly, largely because of less skid resistance. Frequent adjustment of vehicle speed could result in a relatively high magnitude of spectral density function in the high-frequency region, but magnitude in the low-frequency region may not change in a non-rain situation because macroscopic characteristics of the speed curve may not show much difference if rain is not heavy. Thus, the shape of spectral density characteristics could be used in analyzing rainy weather impact. A suitable way to identify curve shape is use of normalized spectral density curves. Figures 12, 13, and 14 show normalized spectral density char-

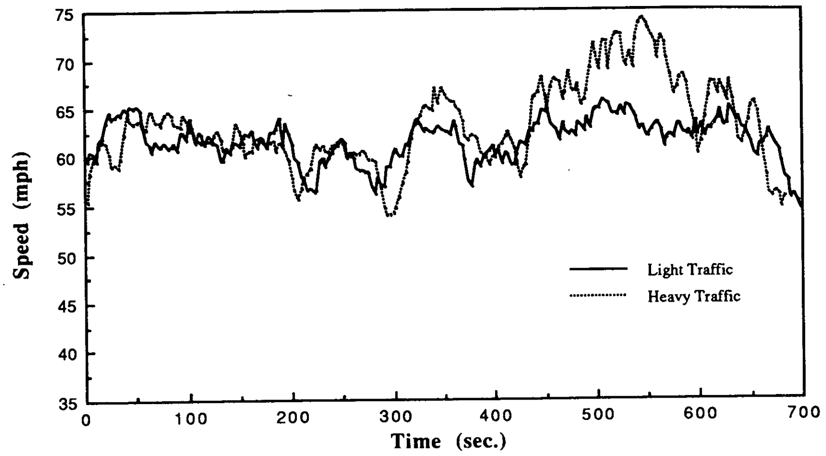

FIGURE 4 Speed sequence collected from Test Site 1 (dry, all lanes).

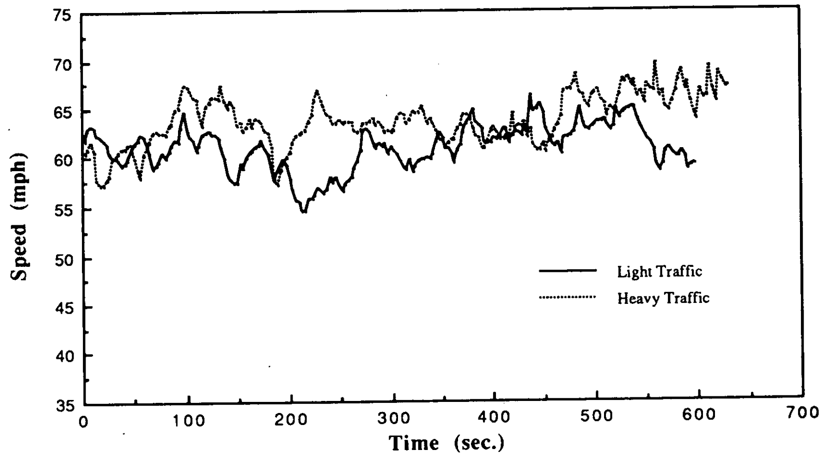

FIGURE 5 Speed sequence collected from Test Site 2 (dry, all lanes).

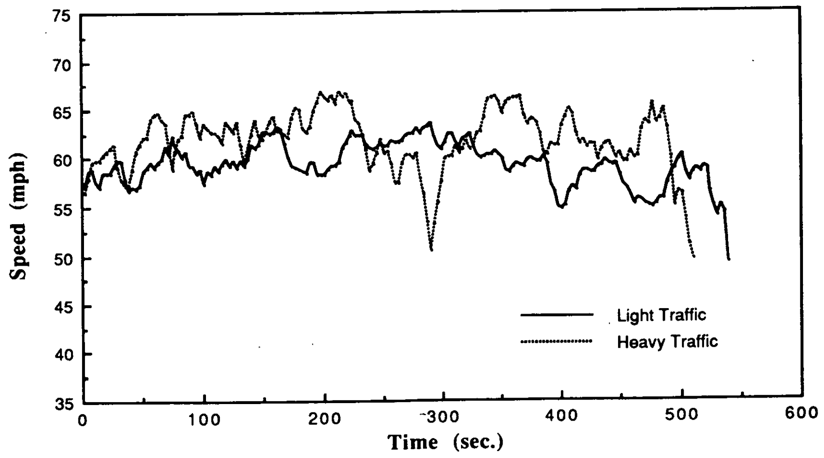

FIGURE 6 Speed sequence collected from Test Site 3 (dry, all lanes).

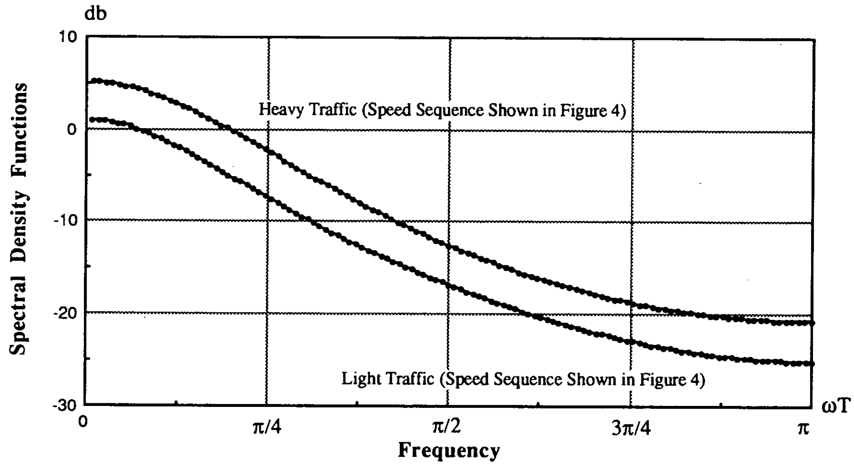

FIGURE 7 Spectral density functions of speed sequences under light and heavy traffic conditions (Test Site 1, dry, all lanes).

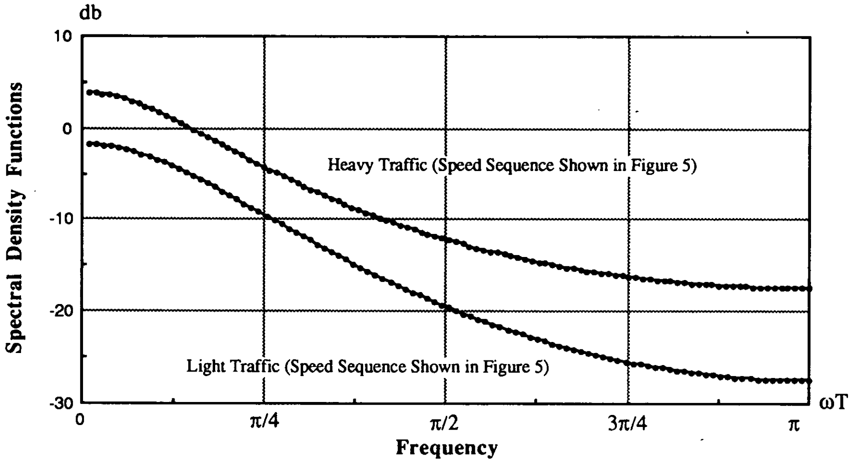

FIGURE 8 Spectral density functions of speed sequences under light and heavy traffic conditions (Test Site 2, dry, all lanes).

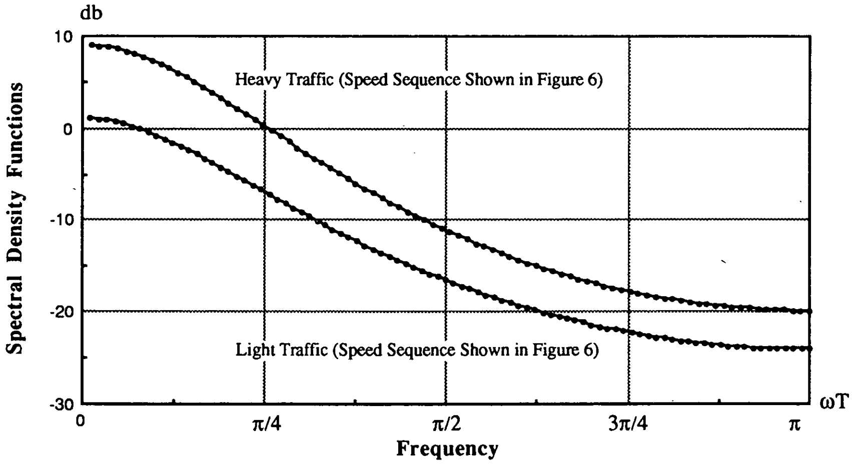

FIGURE 9 Spectral density functions of speed sequences under light and heavy traffic conditions (Test Site 3, dry, all lanes).

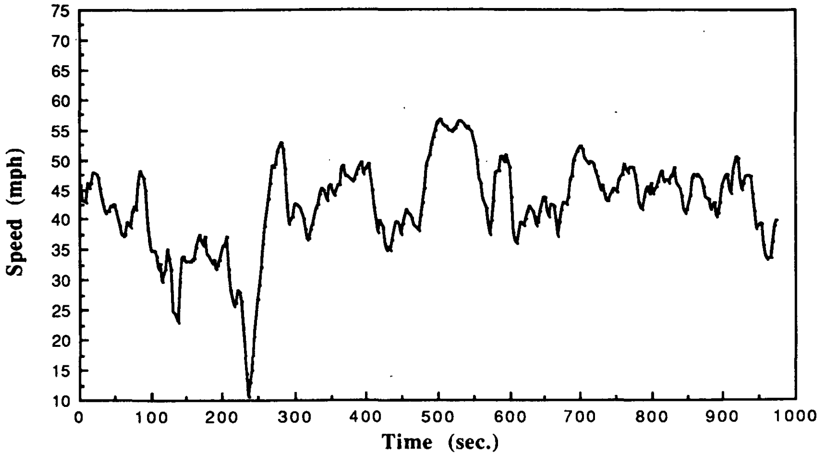

FIGURE 10 Speed sequence collected from Test Site 1 (very heavy traffic, dry, all lanes).

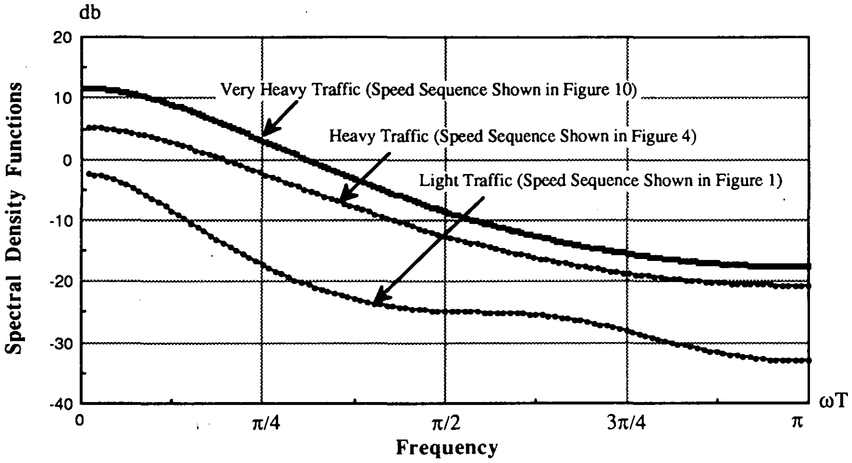

FIGURE 11 Spectral density functions of speed sequences under light, heavy, and very heavy traffic conditions (Test Site 1, dry, all lanes).

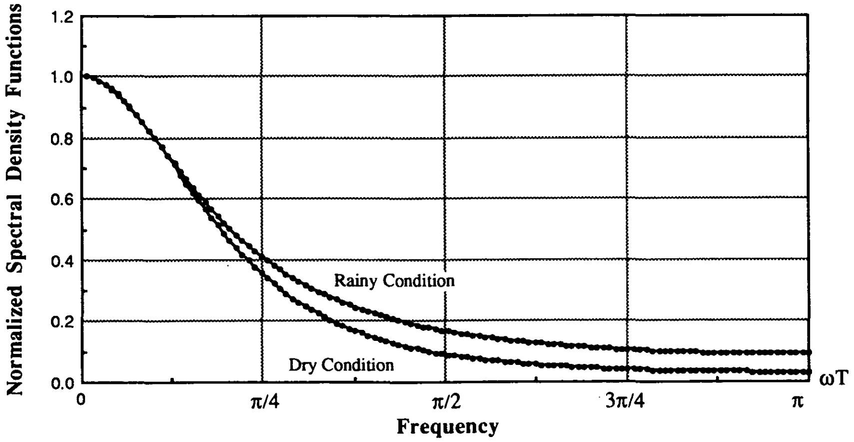

FIGURE 12 Normalized spectral density functions of speed sequences under rainy and dry conditions (Test Site 1, light traffic, all lanes).

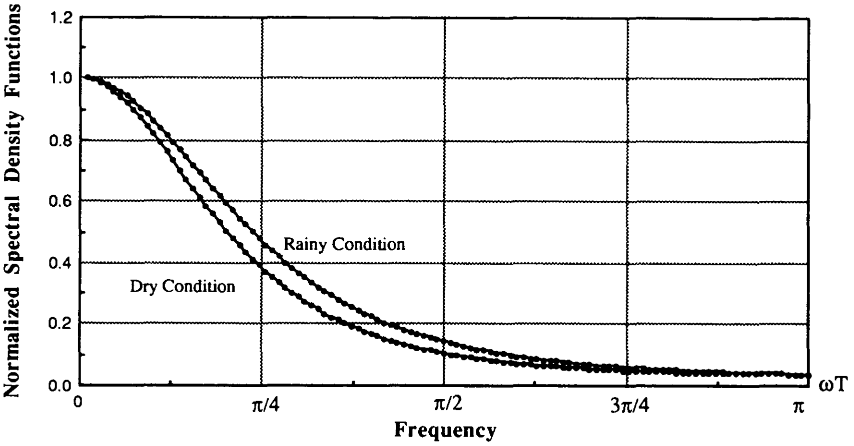

FIGURE 13 Normalized spectral density functions of speed sequences under rainy and dry conditions (Test Site 2, light traffic, all lanes).

acteristics under rainy and dry conditions, with speed data collected from Sites 1, 2, and 3. From these graphs, it is apparent that spectral density characteristics of vehicle speed under light rainy and dry weather do not differ significantly (i.e., driver behavior in terms of speed is not significantly affected by wet pavements). However, during field testing, no heavy rain occurred, and the results may not be applicable to such conditions.

Ramp Impact on Vehicle-Speed Density Characteristics

Vehicles entering from a ramp significantly affect speed characteristics of vehicles already in a freeway. In recent years, research has been done on macroscopic characteristics of ramp impact in the time or space domain. One objective of this study was to evaluate vehicle-speed spectral density characteristics affected by vehicles entering from ramps during a light-traffic condition. It was assumed here that vehicles staying in the right lane were more affected by entering vehicles than vehicles that could change lanes when approaching ramps. Two cases were considered. First, the testing vehicle was allowed to change lanes to avoid ramp impact. In the second, the testing vehicle was directed to stay in the right lane no matter how bad traffic was, and when vehicle speed approached zero the test was considered "fail." Field tests were conducted at Test Sites 1, 2, and 3, and corresponding normalized spectral density functions are shown in Figures 15, 16, and 17, from which differences between "right lane" and "all lanes" can be identified.

Spectral Analysis of Driver Behavior

The tests discussed so far were based on speed characteristics controlled by a specified driver called Driver A. However, another driver might behave differently—some drivers control vehicles in an aggressive manner and others defensively. In the frequency domain, differences in driving behavior can be spotted. Conceptually, an aggressive driver adjusts his speed more often and more quickly under various traffic conditions

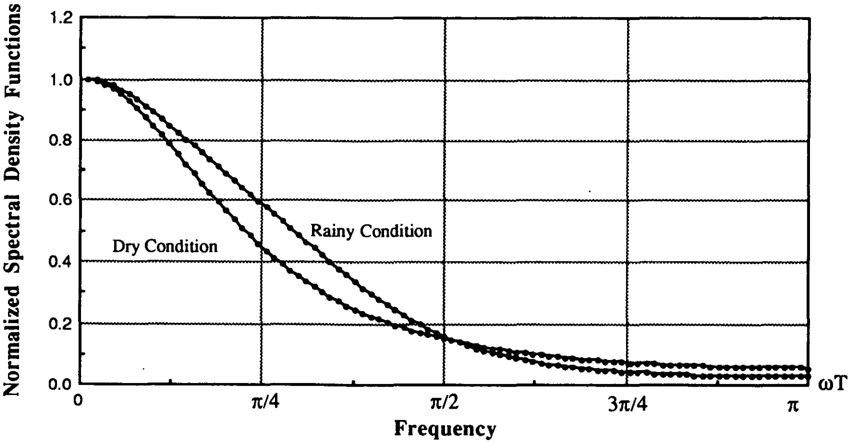

FIGURE 14 Normalized spectral density functions of speed sequences under rainy and dry conditions (Test Site 3, light traffic, all lanes).

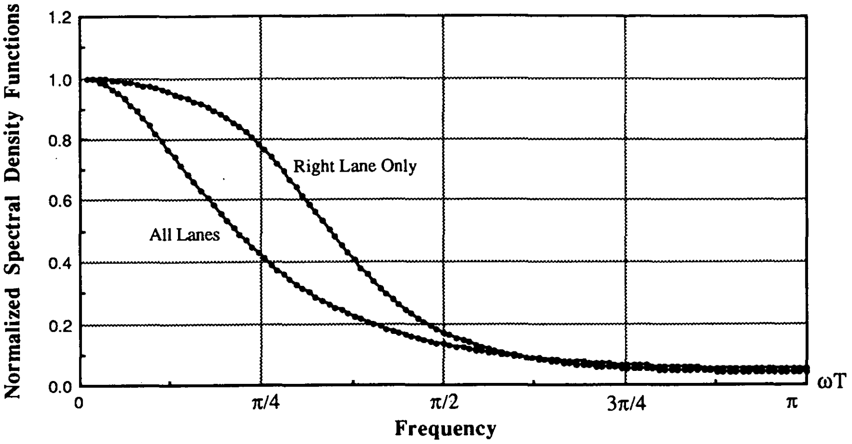

FIGURE 15 Normalized spectral density functions of speed sequences under right lane and all lane conditions (Test Site 1, light traffic, dry).

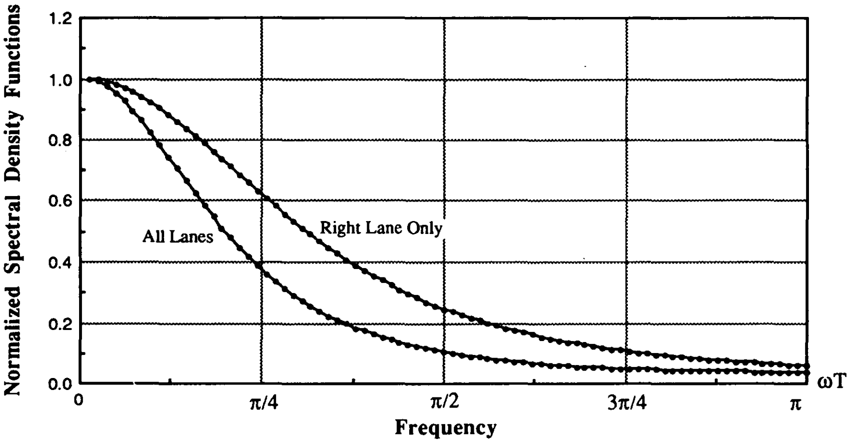

FIGURE 16 Normalized spectral density functions of speed sequences under right lane and all lane conditions (Test Site 2, light traffic, dry).

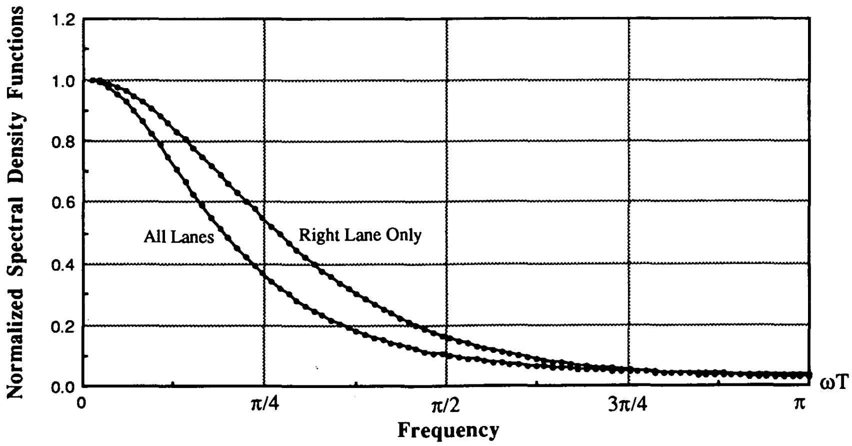

FIGURE 17 Normalized spectral density functions of speed sequences under right lane and all lane conditions (Test Site 3, light traffic, dry).

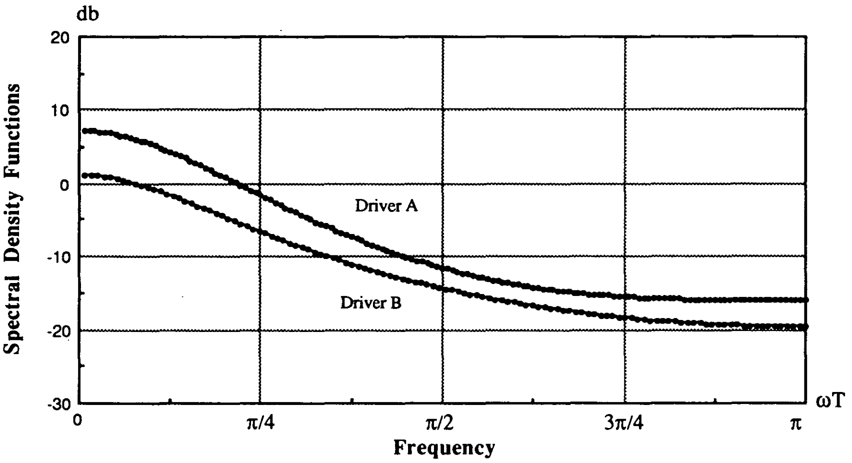

FIGURE 18 Spectral density functions of speed sequences resulting from Drivers A and B (Test Site 1, light traffic, dry, all lanes).

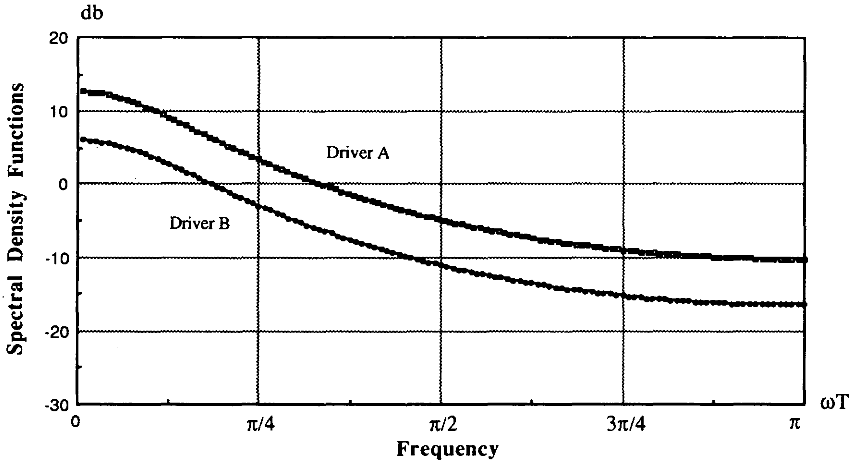

FIGURE 19 Spectral density functions of speed sequences resulting from Drivers A and B (Test Site 1, heavy traffic, dry, all lanes).

than a defensive driver, resulting in higher spectral density magnitude in the whole frequency range. Field tests were conducted at Site 1 to examine this assumption. Two drivers were selected from the research staff, and traffic condition (heavy traffic and light traffic) was considered. Figures 18 and 19 show differences between spectral density characteristics of Drivers A and B under heavy and light traffic conditions. From these graphs, Driver A had a higher spectral density magnitude than Driver B, meaning that Driver B controlled his vehicle more defensively than Driver A. However, this difference is smaller when traffic is light compared with when traffic is heavy.

CONCLUSIONS

1. The spectral analysis technique has been accepted in many engineering areas, but not widely applied or evaluated in transportation engineering. In fact, in addition to the time and space domains, spectral analysis provides another analytical alternative. Some problems that cannot be solved in those domains may be solved easily in the frequency domain.

2. Individual vehicle speed is a stochastic process. If data sampling is limited to a certain time period, this process can be assumed to be symptomatically stationary and approximately normally distributed without obvious constant trends. This assumption makes nonlinear spectral estimation methods applicable.

3. The study reported reflects only initial research results showing how the models work. More effort is needed to evaluate these traffic impacts.

4. Most current vehicle-speed-related research is based on "point detection" or "section detection" (i.e., the mean value of measured speeds is taken at the main variable). In this way more important information is averaged. In fact, such information can be obtained from the detection of the dynamic

speed process, which is called line detection. The technique discussed in this paper belongs to line detection.

5. Data collected from line detection can be analyzed in the time/space domains. Analysis in the frequency domain has been widely used in continuous and discrete control systems and signal evaluation. The spectral analysis technique discussed here can be used to assess highway level of service, traffic congestion, and safety of the traveling public. This technique can also be used in detecting traffic incidents and traffic control, such as in Intelligent Vehicle Highway Systems. However, further research must be conducted to apply spectral analysis techniques to these areas.

6. MESE is one of the spectral estimate methods. For spectral analysis, other estimate methods could be used. Many computer software packages are available.

ACKNOWLEDGMENTS

William G. Roth performed instrumentation and data reduction work for this study. Field tests were conducted by Robert W. Rider, Andrew A. Dagostino, and Edward W. Bikowitz.

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The contents of this paper reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of FHWA. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Traffic Law Enforcement.

Speed Estimates for Roadway Design and Traffic Control

P. N. SENEVIRATNE AND M. N. ISLAM

Estimates of expected 85th percentile speed, $E(P_{85})$, are essential for highway engineering and traffic control. Often, however, $E(P_{85})$ differs from observed P_{85} after the facility is fully operational because of several reasons, including the errors stemming from the model and statistical uncertainty. Data from a series of spot speed surveys suggest that the proportion of all vehicles contravening the respective limits on local roads, arterials, and freeways is as high as 90 percent, and when heavy vehicles are considered separately, the exceeding proportions change little, if any. It is suggested that this is rendering control devices, which are in certain cases based on inaccurate estimates of $E(P_{85})$, inadequate for the prevailing operating conditions. While errors from approximating speed distributions by the normal model (model uncertainty) may be easily minimized, unavailability or unreliability of data due to constraints surrounding transportation agencies and statistical uncertainty is not easily eliminated by the conventional practices. Bayesian estimates based on sample and prior (assumed or subjective) parameters are an effective method of reducing errors and data requirements.

Despite the growth in traffic volumes, speeds on all classes of roadway in Quebec have been gradually increasing. The average highway speed, for example, has increased by about 3 km/hr (2 mph) between 1987 and 1989, whereas the average proportion of drivers exceeding the 100-km/hr (66-mph) speed limit on highways has increased from approximately 70 percent in 1981 to 75 percent in 1989 (*1*). Similar trends have also been noted in the United States (*2*) and Sweden (*3*).

Although the increases are not always statistically significant (*1*), and the likelihood of continued increases are small as evident from Sweden (*3*) and Britain (*4*), some studies have suggested that lower well-controlled operating speeds can reduce accident severity and, hence, lead to large safety benefits. The arguments for lower speeds are based primarily on the premise that the existing speeds in many cases exceed design values by significant margins. It has been observed many a time that, in the absence of continued surveillance, most drivers adjust to a speed perceived to be in accordance with the prevailing environmental and roadway conditions. Under ideal conditions, the average speed is close to the original design/control speed, with or without surveillance. The problem, however, is that the design parameters could change over time, even though the speeds may not, and thereby expose more than the anticipated share of drivers to risk. Thus, it is the responsibility of the transportation agencies to ensure that the prevailing standards meet the standards demanded by the traveling public, or, if not, to take appropriate action to change either the designs or driver behavior.

As far as the departments of transportation are concerned, such an endeavor would mean a continued assessment of speed profiles, requiring additional resources of equipment and personnel. But when the resources are limited, the speed profile analyses have to be based on statistical approximations and sampling techniques. Transportation agencies often use approximations such as control station-based expansion factors for forecasting traffic volumes, historic material performance data for estimating pavement life, and so forth. Some approximations are even based on new probability concepts such as Bayesian approaches that use historical data, engineering judgment, or sample data to increase the accuracy of parameter estimates.

When data are too scarce for detailed analyses, the assumption that spot speeds at any given site are symmetrically distributed and the use of the normal approximation are common. They permit the estimation of a design/control speed for roadway geometry or traffic control devices according to a predetermined level of acceptable risk. In this paper, the widely used critical speeds, the rationale behind these speed values, and their estimation are discussed. The discussion is presented in two parts. The first examines the speed distributions in three classes of urban roadway while emphasizing the need to periodically review facility performance in relation to the existing safety standards dictated by traffic control devices and roadway geometry. In the second part, a methodology that would enable transportation agencies with resource constraints to perform the periodic reviews using random sampling of spot speeds is proposed.

SIGNIFICANCE OF CRITICAL SPEED

The critical speed in the present case refers to the speed value used in the computation of either the geometric variables such as radii of curvature or stopping distances for traffic control purposes. For traffic control purposes, the standard manuals and handbooks (*5–7*) suggest the 85th percentile speed (P_{85}) as the appropriate critical speed, which is the speed at the point when speeds are "dispersed" (*5*). In statistical terms, this speed limits the probabilistic risk (failure or operating conditions outside the safe range) to 15 percent.

The critical speed for geometric design, on the other hand, is not as well defined as for traffic control. Yet, it is implied in the design manuals that it should be set in relation to the expected operating speed of the design vehicle (*6*). In some instances, it may be the highest expected speed or a speed that reflects the acceptable probabilistic risk (5 or 10 percent). Thus, it is imperative that speeds be routinely monitored to

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ensure that they fall within the limits dictated by prevailing roadway geometry and various traffic control devices, and to take appropriate steps to either regulate the speeds or alter the designs.

Unfortunately, most transportation agencies are limited by resources to perform the periodic analyses and, where necessary, to calibrate the system elements to accommodate the demand at the specified level of safety. As mentioned hitherto, the normal approximation permits the estimation of $E(P_{85})$ or the critical design speed at the desired level of significance directly from statistical tables. However, if traffic streams do not have symmetrically distributed speeds or the distribution parameters are estimated from small samples, such an approximation would introduce a certain bias into the estimates, which in turn could impair one's judgment on the adequacy of a control device in relation to safety. This issue is discussed in the following section as it relates to the metropolitan Montreal area in Quebec.

DATA

The discussions and examples in this paper are based on surveys of spot speeds on several urban arterials, freeways, and local (residential) streets in Montreal. Spot speeds were measured using radars during off-peak hours over a period of 3 years between 1989 and 1991. The survey sites consisted of 29 school/residential zones, 10 sites on divided six-lane arterials, and 5 sites on six-lane freeways. The weather during all survey periods was fine, and the surfaces were dry with no irregularities in the traffic streams.

To ensure that the samples are homogeneous, sites in each class of road were chosen at random but have similar characteristics in terms of adjacent lane use, traffic volume, geometry, and average intersection spacing. For instance, the arterials were similar in that the divisions were all low medians, and the adjacent land use was either mixed residential and recreational or mainly residential, but with no direct access to the arteries. The arterial lane widths differed slightly in that some had 3.5-m lanes whereas others had 3.75-m lanes. However, this was not considered sufficient to cause significant differences in speeds. All freeways, on the other hand, had 3.75-m lanes, and the residential streets were all two-lane streets in the vicinity of schools. All sites were tangent sections, with no curves in the immediate vicinity that would influence speeds.

The sample freeway sections included one speed zone of 80 km/hr, two zones of 90 km/hr, and two 100-km/hr speed zones. The arterial and school zone speed limits were 50 and 30 km/hr, respectively. The posted limits were clear and within 500 m of the sample sites.

STATISTICAL TESTS

A random sample of recorded spot speeds was chosen, and the relative frequency distribution at each site was plotted. Three probability distribution functions (normal, log-normal, and shifted-gamma) were then fitted to the observed data at each site, and a chi-square goodness-of-fit test was performed. All three distributions fitted the observed data at most sites, and one could have accepted any of them at the 5 percent level of significance. The critical level of significance (the level of significance at which a particular distribution could be rejected), however, varied from site to site, with log-normal fitting the distributions of local streets best and the normal distribution showing the best fit in the other two types of roadway. Despite this slight difference, the normal distribution was assumed to be a reasonable approximation in all cases. A summary of the statistical analyses at selected sample sites is given in Table 1.

Statistics in Table 1 also point to some distinguishable characteristics of speed distributions of the different types of roadway. First, the freeways have generally lower coefficients of variation and a standard error of mean than local roads. According to the statistical tests, the mean speeds of the sample sites are also normally distributed. The small standard error of mean speed when sections with the same speed limit and roadway conditions are grouped together is an indication that drivers in the freeways behave much the same way throughout the study region. The standard deviations of speed, on the other hand, are almost invariable from one site to another, and the statistical tests indicated that the differences are insignificant at the 5 percent level. Hence, the population standard deviation could be considered equivalent to the standard deviation at a given site.

The population means of the other two classes of roadway have much wider distributions, as evident from the standard errors of mean. Here too, the differences in standard deviations were insignificant, and the standard deviation of the local street population and arterial population can be approximated by that of any particular site.

The second point of interest is the difference in observed P_{85} speed and the expected 85th percentile speed, $E(P_{85N})$, computed from normal tables, particularly if the distribution showed signs of skewness. In most cases, the difference was less than 3 km/hr, which is an indication that the normal approximation does not result in large errors.

To illustrate this case, consider the computation of the expected 85th percentile speed on the basis of the normal approximation:

$$E(P_{85N}) = \text{mean speed} + 1.04\ (\text{standard deviation of speed}) \qquad (1)$$

However, as seen from the root mean square error of 1.83 percent and Figure 1, certain factors other than skewness seem to cause the marginal differences in observed and expected values. Although a relation between error and any other statistic was not evident in the present case, it was felt that such modeling uncertainty can be minimized if Expression 1 can be calibrated to fit the observed data.

A multiple regression analysis of the disaggregate data (for each type of road) was performed in this regard. The disaggregate models demonstrated the same high degree of correlation between P_{85} and the distribution parameters (mean and standard deviation) as the aggregate model. Thus, the discussion is based on the aggregate model (valid for all classes of road) below, which was derived after dropping the insignificant regression constant from the original expression.

TABLE 1 Speed Statistics of All Vehicles for Different Classes of Roadway

Site	μ mean	σ s.d.	γ skewness	coeff.of var.	P_{85} obs.	$E(P_{85N})$	speed limit	% over limit
Local Roads								
Mcgregor	54	8.5	0.15	0.16	64	63	30	92
Ramzey	43	5.8	.17	0.13	48	49	30	90
Simpson	44	6.8	.04	0.15	52	51	30	100
Douglas	48	7.5	.34	0.16	56	56	30	100
29 sites	48	8.0						
Std. error of mean of all sites = 6.0								
Arterials								
Sources	67	7.1	.24	0.11	74	74	50	100
St. Jean	65	7.9	.22	0.12	73	73	50	95
St. Charles	58	7.4	-.12	0.13	66	66	50	82
10 sites	66	7.5						
Std. error of mean of all sites = 4.5								
Freeways								
A. 20 #1	94	11.5	.48	0.12	106	106	80	89
A. 20 #2	94	11.9	1.33	0.13	106	106	80	89
A. 40 #2	106	11.0	.47	0.10	114	117	100	65
A. 13 #1	107	10.1	.48	0.09	115	118	100	78
A. 13 #2	107	9.33	.31	0.09	115	117	100	76
H. 217	94	n/a	n/a	n/a	104	105	90	62
8 sites	105	10.8						
Std. error of mean of all sites = 2.2								

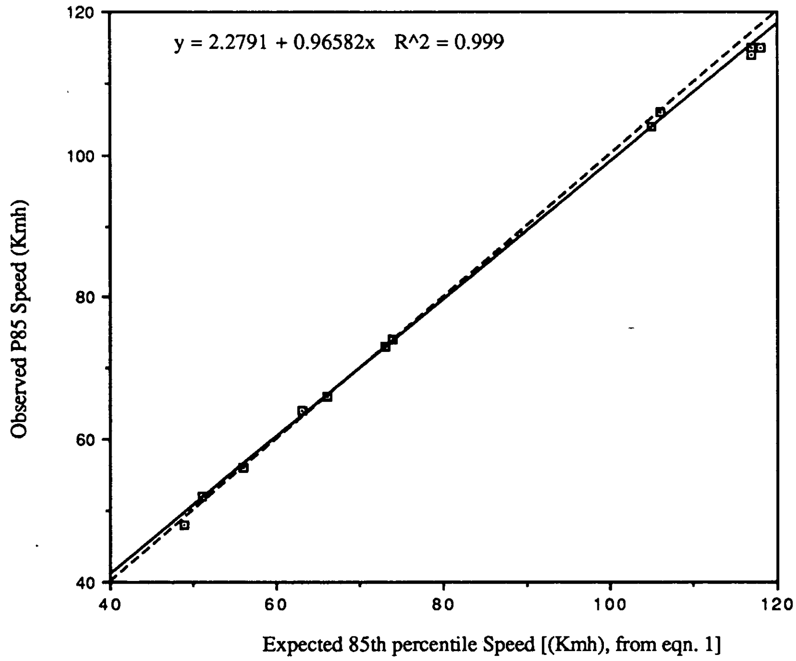

FIGURE 1 Relation between observed and expected critical speed.

$$E(P_{85}) = 0.996(\text{mean speed}) + 1.16(\text{st. dev. of speed})$$
$$(s_e = 0.016) \qquad (s_e = 0.187) \qquad (2)$$

The coefficient of determination (r^2) of 0.998 and the small standard errors of the coefficients suggest that the observed 85th percentile speed is approximately equivalent to $E(P_{88N})$, or the 88th percentile speed on the basis of normal tables. Thus, given accurate estimates of the two speed distribution parameters (mean and standard deviation), errors due to normal approximation could by and large be reduced to a fraction.

The relationship may not necessarily be valid over both time and space. Yet, where there are data that permit the estimation of population distribution parameters for a given roadway type, such a model can be extremely useful in spot speed analyses for safety studies.

CRITICAL SPEED IN RELATION TO CONTROL SPEED

As alluded to earlier, P_{85N} speed is currently the critical (decision) speed in Quebec for posting limits and determining clearance times in traffic signal design and sight distance calculations for street signing and marking. However, the prevailing P_{85} in all classes of roadway differs significantly from the posted limits. Although there is no documented evidence, a limited survey of clearance times and sight distances at a few selected sites indicated that they are based on the posted speed.

The critical speeds used in the original geometric design of arterials and local streets (70 and 50 km/hr, respectively), on the other hand, differed from P_{85} by a somewhat lesser margin than P_{85} from the posted limits. For instance, the study found the share of vehicles exceeding the posted speed limit on freeways during daytime to be approximately 75 percent, which is similar to that reported by Guimont (*1*) following a detailed study of more than 118 locations in the same region. The exceedance probabilities on local streets and arteries considered were even greater at 90 and 92 percent, respectively. The respective percentages of vehicles traveling at speeds greater than the geometric design speed, on the other hand, are comparatively less, but much higher than the preferred 5 to 10 percent in the local streets and arterials.

A simple regression analysis was performed to verify the correlation between observed P_{85} speed and posted speed limit as well as design speed. In both cases, simple linear functions seemed to best describe the relations:

$$E(P_{85}) = 28.76 + 0.88(\text{speed limit})$$
$$(s_e \text{ of regression coeff.} = 0.058) \qquad (r^2 = 0.91) \qquad (3)$$

$$E(P_{85}) = 16.0 + 0.88(\text{design speed})$$
$$(s_e \text{ of regression coeff.} = 0.04) \qquad (r^2 = 0.96) \qquad (4)$$

The U.S. national speed trends quoted in the *Highway Capacity Manual* (*8*) and data from several recent speed surveys conducted by numerous states (*9*) indicate levels of exceedance similar to the level given by Expression 3 at certain speed limits. Therefore, it may be reasonable to suggest that, if the existing posted limits are the underlying design or control speeds, the probabilistic risk at all surveyed sites is currently well below the desired 5 to 10 percent.

On the other hand, if the limits are established independently of critical control and design speeds, for example, to be in accordance with the road class, to maintain uniformity, or to reduce energy, the posted limits may need to be justified with more vigor. Otherwise, in the absence of continued enforcement, one can expect operating speeds of vehicles under normal conditions to be close to the design speed, as suggested by Expression 4.

Evidence of such diversions has been reported by several others. For instance, Spitz (*10*) suggests that speed limit rarely has any effect on vehicle operating speeds. Statistics are cited to demonstrate that both raising and lowering speed limits have very little effect on the P_{85} speed. British experience has shown that there is only a ½-km/hr drop in average speed for every 1-km/hr reduction in speed limit (*11*). However, the P_{85} speed was always found to remain greater than the posted limit, suggesting that speed is a function of the perception of safety as opposed to theoretical safety.

The relations between design speed, posted limit, and $E(P_{85})$ (i.e., Expressions 3 and 4) have certain noteworthy features. First, it is apparent that the difference between the limit and $E(P_{85})$ as well as design speed and $E(P_{85})$ is less significant at higher speeds than at lower speeds. This characteristic supports what Spitz (*10*) has noted; increases in limits may not necessarily result in proportionate increases in operating speeds. Second, either relationship may serve as a rule of thumb for design purposes. For instance, despite the design speed definitions in the standards manuals (*12*), the ideal posted limit and design speed for a given P_{85} speed may be computed from a relation of the form of Expression 3 or 4. These expressions suggest that the control speed and the design speed, respectively, should be approximately 15 percent and 25 percent greater than the speed limit, as shown in Figure 2.

SPEED DISTRIBUTIONS OF HEAVY VEHICLES

The study also examined the speed characteristics of heavy vehicles in relation to automobiles in two of the three classes of roadway. The examination confirmed the revelations of Transport Quebec's study (*1*) that the difference between the mean speed of heavy vehicles and automobiles on freeways and arterials is less than 3 km/hr. Even the P_{85} speeds are not significant at the 5 percent level. Heavy vehicle speed statistics from the present study are given in Table 2.

In view of the larger decision sight distances required, what was noted in the previous section under speed limits and prevailing speeds is of even greater significance to heavy vehicles. With the percentage of heavy vehicles traveling above the posted limit being over 80 percent on certain freeways and 90 percent on arterials, there is all the more reason to be concerned about safety.

BAYESIAN APPROACH

From the point of view of both traffic control and geometric design, the results of the preceding analyses raise some serious

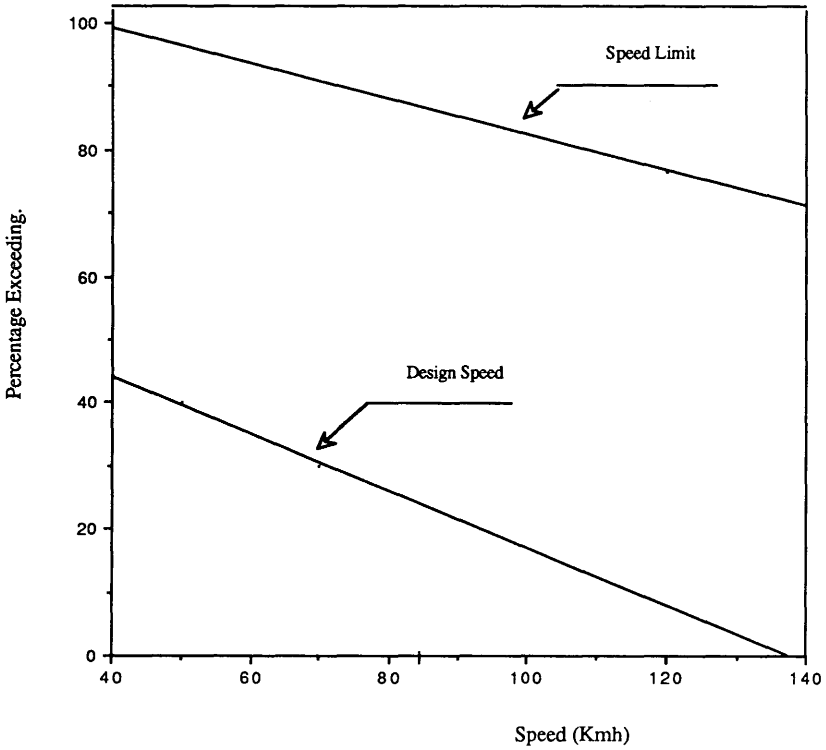

FIGURE 2 Approximate percentages exceeding design speeds and speed limits.

safety concerns. Since the exceedance probabilities are far greater than the originally anticipated levels, it may now be time to reexamine traffic control devices and geometry and make necessary adjustments where there are significant differences. The cost of data gathering through conventional techniques, however, still remains the fundamental deterrent. It is unlikely that all transportation agencies will soon have access to the high-tech data gathering and reducing equipment that would permit fast and inexpensive treatment of large data samples. Under the circumstances, the Bayesian approach is an effective means of addressing statistical uncertainty in parameter estimates.

As with many aspects of transportation engineering, spot speed analyses require engineers and analysts to make certain assumptions based on limited data, particularly with regard to the distribution parameters. However, the widely used classical approach does not contain a formal process through which these judgmental beliefs can be incorporated in the estimates. One can only express the estimation error in relation to the sample size and population variance (i.e., σ^2/n). The Bayesian approach, on the other hand, assumes that the parameters are random variables and permits information from external sources to be formally combined with the data to minimize the uncertainty of data due to small samples.

In this study, we adopted the Bayesian approach that requires a prior knowledge (subjective judgment or experience with similar sites) of the speed distribution mean (μ'), the standard error of this mean ($\sigma_{\mu'}$), and standard deviation (σ') of speed for the class of road examined. With this approach, the sample distribution parameters m and s estimated (using the classical approach) from a few spot speed measurements at a site can be combined with the prior knowledge to obtain an estimate closer to the true mean at the site and, if necessary, to obtain the confidence interval for the mean.

TABLE 2 Speed Statistics of Heavy Vehicles for Freeways

Site	μ mean	σ s.d.	γ skewness	coeff.of var.	P_{85} obs.	$E(P_{85N})$	speed limit	% over limit
Freeways								
A. 20 #1	88	7.5	.48	0.09	98	96	80	80
A. 20 #2	89	9.86	1.30	0.11	99	95	80	85
A. 40 #1	93	7.51	-0.37	0.05	102	101	100	16
A. 40 #2	99	5.95	-0.42	0.06	105	108	100	48
A. 13 #1	95	7.81	-0.52	0.08	105	103	100	25
5 sites	93	7.73						
Std. error of mean of all sites = 4.02								

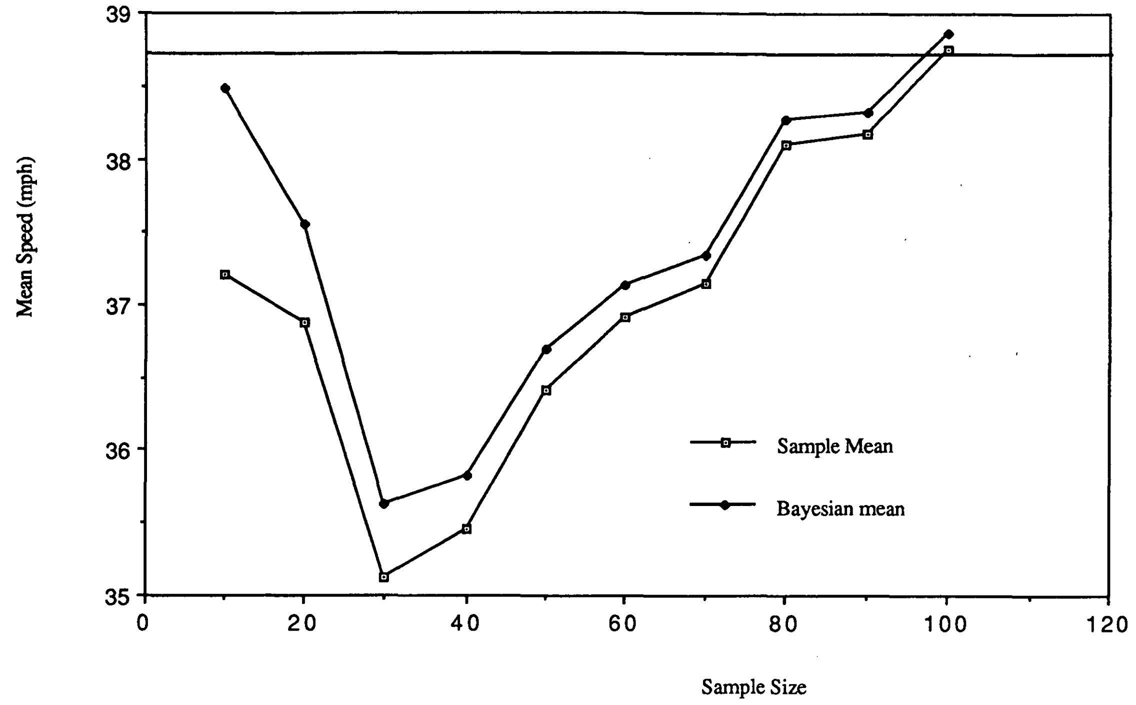

FIGURE 3 Difference between sample and Bayesian means.

The newly estimated parameters, called the posterior/Bayesian mean and standard deviation, are expressed as follows (*13*):

$$\mu'' = \frac{m(\sigma^2_{\mu'}) + \mu'(\sigma'^2/n)}{(\sigma^2_{\mu'}) + (\sigma'^2/n)} \tag{5}$$

$$\sigma'' = \sqrt{\frac{(\sigma^2_{\mu'})\,(\sigma'^2/n)}{(\sigma^2_{\mu'}) + (\sigma'^2/n)}} \tag{6}$$

where μ'' and σ'' are the Bayesian mean and standard deviation of mean, respectively.

In the present case, prior knowledge is needed of the values of μ', $\sigma_{\mu'}$, and σ' for each of the three classes of road. Thus, if a small sample of speed data can be obtained for a given road section having characteristics similar to the constituents of the prior data base, the true (population) parameters of this road section are likely to be closer to μ'' and σ'.

The difference between the Bayesian estimate and the classical estimate with different sized samples from a randomly chosen survey site is shown in Figure 3. It is clear that the Bayesian estimates are closer to the true mean speed at the site based on a sample of 150 readings, and the difference becomes smaller as the sample size increases.

APPLICATION OF BAYESIAN APPROACH

Consider a site in the local street network having similar characteristics to those in the prior data base. To illustrate the concept, two samples of 10 speed readings are chosen at random from a set of 100 readings. The basic statistics (mean,

TABLE 3 Input Data for Illustrative Example

	Sample 1	Sample 2	All Data
sample size (n)	10	10	100
sample mean (m)	54	56	52
sample std. dev. (s)	14	13	12
coefficient of skew.	0.129	0.114	0.122
coefficient of variation	0.26	0.23	0.23
Observed P_{85}	-	-	66
$E(P_{85N})$ (eqn 1)	69	70	64
$E(P_{85})$ [eqn.2]	70	71	66
Bayesian mean	53	55	-
$E(P_{85N})$(eqn 1) Bayes	61	63	-
$E(P_{85})$ [eqn.2] Bayes	62	64	-

standard deviation, skewness coefficient, and coefficient of variation) are given in Table 3.

The statistics in the "all data" column are computed on the basis of the 100 readings. Prior information below for local roads, on the other hand, is taken from Table 1: $\mu' = 48$ km/hr, $\sigma' = 8$ km/hr, and $\sigma_{\mu'} = 6$ km/hr.

For Sample 1, the posterior (Bayesian) parameters according to Expressions 5 and 6, respectively, are approximately $\mu'' = 53$ km/hr and $\sigma''_{\mu} = 2.33$ km/hr.

Likewise, for Sample 2, the posterior parameters are estimated to be 55 and 2.33 km/hr, respectively. Thus, in both instances, the posterior mean is closer than the sample mean to the population mean (based on 100 readings) of 52 km/hr. Likewise, compared with $E(P_{85N})$ based on sample data, the same computed with the Bayesian mean and population standard deviation of 8 km/hr is closer to observed P_{85} of 66 km/hr in both cases.

The $E(P_{85})$ obtained when Bayesian parameters are substituted in Expression 2 for the two samples (62 and 64 km/hr) are both closer to the observed P_{85} than 71 and 70 km/hr obtained with the sample data.

CONCLUSIONS

Prevailing operating speed of vehicles in all three classes of roadway examined in this study exceeds the speed permitted in relation to the existing traffic control measures such as signal lights, road signs, and so forth. Although the percentage of vehicles traveling above original design speed is less than the percentage traveling above the control speed (speed limit), it is well above the suggested value of 5 to 10 percent. Hence, there is an urgent need to perform an extensive survey of speed conditions.

The data needed to perform such an extensive survey are expensive and time-consuming to collect. Thus, it was suggested that some statistical approximations and sampling procedures be used. Uncertainty and consequent errors, which stem largely from approximating speed distributions by the normal model, are negligible if the critical speed is estimated as a function of the distribution parameters (e.g., Expression 2), with coefficients estimated from observed data as opposed to normal tables. Expression 2 can explain 99 percent of the variation as compared with approximately 93 percent by Expression 1. The accuracy, however, is also dependent on the input variables to the regression model.

For cases with small samples, it is shown that the Bayesian approach could be used to increase accuracy. Even in instances where small samples are inevitable due to problems of data acquisition or time limitations, the Bayesian approach can be extremely useful as long as some prior information is available.

ACKNOWLEDGMENTS

The authors wish to thank Massoud Javid and Carina Persson for assisting with data collection and analysis during the first 2 years of this study. This research was funded in part by the Natural Sciences and Engineering Research Council of Canada and the Utah Center for Advanced Transportation Studies.

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Publication of this paper sponsored by Task Force on Statistical Methods in Transportation.

Impact of Differential Speed Limits on the Speed of Traffic and the Rate of Accidents

NICHOLAS J. GARBER AND RAVI GADIRAJU

After the enactment of the Surface Transportation and Uniform Relocation Assistance Act in 1987, several states changed the speed limit on rural Interstate highways from 55 to 65 mph. Some of these states have restricted truck speeds by imposing differential speed limits (DSLs). As a result, the maximum speed limit for trucks is 55 mph and that for passenger cars is 65 mph. The objective was to reduce the impact of the increased speed limit on accidents involving trucks. However, the extent to which this strategy has been successful in achieving the objective has not been documented by field data. The nature and extent of the effects of DSLs on vehicle speeds and accident characteristics were assessed. Speed and accident data at study sites in California, Michigan, Maryland, Virginia, and West Virginia were used. Data from Interstates 64, 77, and 81 that traverse Virginia and West Virginia were used for a direct comparison of the DSL. Statistical analysis of the data indicated that, in states where the DSL was imposed (65 mph for nontrucks and 55 mph for trucks), the mean speeds of passenger cars or vehicles other than trucks increased only from 1 to about 4 mph in response to a 10-mph increase in the speed limit. However, there was no significant increase in the mean speed of trucks. Also, following the increase of the speed limit to 65 mph for vehicles other than trucks, speed fluctuations within the traffic stream decreased. On the other hand, speed variances for all vehicles were still higher on Virginia highways with DSL (65/55 mph) compared with those for similar highways in West Virginia operating under 65/65 mph. There is no evidence that the increase in the maximum speed limit to 65 mph for passenger vehicles on the rural Interstate systems in the states studied has directly resulted in a significant increase in fatal, injury, or overall accident rates.

At the time of the severe oil shortage in the early 1970s, a speed limit of 55 mph was imposed in an effort to reduce fuel consumption. With the easing of the oil crisis in the early 1980s, the benefits of a blanket 55-mph speed limit were questioned. Compliance with the 55-mph speed limit was decaying, leading to a concern that the safety of U.S. highways would be affected (*1*). After the enactment of the Surface Transportation and Uniform Relocation Assistance Act on April 2, 1987, most states changed their speed limits from 55 to 65 mph on rural Interstate highways. However, there was concern among some decision makers that trucks traveling at 65 mph might increase the potential of accidents between trucks and other types of vehicles. The imposition of a lower speed limit for trucks, usually referred to as a differential speed limit (DSL), was identified as one of the ways of reducing the interaction between trucks and other vehicles. The underlying concept of DSL is that for any given speed, a truck takes more time to decelerate to a lower speed and requires more stopping distance than a passenger car. Hence, the speed differential can compensate for the disparity in operating characteristics by making braking distances more compatible. On the basis of this theory, some states adopted the DSL to lessen the effect of raising the speed limit.

Proponents of the higher speed limit for trucks point out the economic benefits of higher limits and contend that enforced speed differentials may generate more accidents and hence increase the propensity for certain categories of accidents such as rear-end collisions, thereby resulting in an increase in fatal crashes involving trucks (*2*).

However, these theories have not been adequately investigated using actual field data. To provide the information required to evaluate and compare the different speed limit strategies, the effects that the 65/65- and 65/55-mph limits have had on the speed of traffic and accident patterns were investigated.

A study in Maryland found that at sites with a posted differential of 10 mph, the actual difference between car and truck speeds was less than 6 mph (*3*). The higher passenger car speed limit associated with a DSL contributed to a higher percentage of compliance (62 percent) than was the case with equal (55/55-mph) limits (40 percent). Elmberg studied the effect of posted speed limits on drivers' speeds (*4*). Elmberg's results indicated that drivers paid little if any attention to the posted speed limits and that drivers chose a speed that they themselves considered appropriate for the prevailing conditions. An important corollary to these results is the finding by Garber and Gadiraju that the difference between the design speed and the posted speed limit has a significant effect on speed variance in that speed variance increases rapidly when this difference is less than 5 mph or greater than 10 mph. That study also showed that accident rates increase with increasing speed variance for all classes of roads (*5*). The Maryland study also noted that although speed variation can be brought about by enforced differential truck speed limits, the existence of a posted DSL was not related to the occurrence of truck accidents. The study also suggested that lower rates of truck accidents could be expected with higher speed limits and hence recommended an increase of truck speed limits from 55 to 60 or 65 mph on highways carrying a sizable fraction of trucks. A simulation study carried out in Virginia also concluded that no safety benefits were observed by imposing a DSL. On the contrary, it was reported that there was a potential for an increase in accident rates, especially on highways with high AADT and a high percentage of trucks (*2*).

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PURPOSE AND SCOPE

The primary purpose of this study was to determine whether the imposition of a DSL on a rural Interstate highway will result in significant changes in the speed of the traffic and the type and number of accidents on the highway. Although the study was limited to the states of California, Maryland, Michigan, Virginia, and West Virginia, the results can be generalized because of the varied locations of these states.

The specific objectives of the study were to

- Determine the effect of increasing the speed limit to 65 mph for passenger cars on the speeds of passenger cars and trucks and on accident patterns;
- Investigate the effect of a DSL on speed dispersion and the difference between mean speeds of trucks and passenger cars, accident rates and the severity of accidents, and different categories of accidents and various types of collisions; and
- Compare the relative benefits of the 65/55- and the 65/65-mph speed limits.

METHODOLOGY

Selection of Study Sites

The selection of sites for this study was based on the premise that data from a few sites from states located in different parts of the country would give more representative results than data from many sites in one or two states in the same area of the country. For comparisons, two sets of sites were chosen. The first set consisted of test sites and control sites. Test sites were segments of the Interstate routes on which the posted speed limit was increased, and control sites were those sections on which the speed limit remained at 55 mph. Typical control sites were Interstate segments near metropolitan areas and other comparable federal routes running parallel to test sites. A total of 11 sites at which extensive data had been collected before and after the speed limit increase were selected. There were three in California (one test and two control), three in Michigan (one test and two control), four in Virginia (two test and two control), and one control site in Maryland. The data from the first set of sites were used to investigate the effect of raising the speed limit to 65 mph for vehicles other than trucks.

The second set consisted of sites on routes I-66, 1-77, and I-81 that traverse both Virginia (with DSL) and West Virginia (without DSL). This facilitated the direct comparison of the effect on accident characteristics of the 65/55-mph speed limit with that of the 65/65-mph speed limit. Unfortunately, it was not possible to obtain "before" speed data at the West Virginia sites. The comparison was therefore made on the "before" and "after" accident rates but only on speed data from the period after the DSL went into effect in Virginia.

Data Collection

Speed Data

The speed data were collected during 24 hr of continuous monitoring. For direct comparison, speeds were recorded before and after the change in speed limit. Tables 1 through 4 give the speed statistics at the test and control sites for the

TABLE 1 "Before" and "After" Speed Data for California Study Sites

PERIOD	VEHICLES	SPEED LIMIT	VOLUME (ADT)	MEAN SPEED (MPH)	STND DEVN	85th % SPEED	% IN PACE	% OVER LIMIT
			Test Section – Interstate 5 Near Williams					
"BEFORE"	CARS	55	3921 SB	66.0	6.4	72	63.3	95.3
	TRUCKS	55	2918 SB	62.7	6.3	68	72.6	89.9
	ALL VEHICLES	55	6839 SB	64.7	6.6	71	65.5	93.0
"AFTER"	CARS	65	5835 SB	67.2	6.3	74	64.5	69.1
	TRUCKS	55	2827 SB	61.2	5.9	67	72.4	21.7
	ALL VEHICLES	65/55	8662 SB	65.2	6.8	72	58.0	53.5
			Control Section A – Interstate 5 in Sacramento					
"BEFORE"	CARS	55	30192 SB	62.7	5.8	69	65.6	93.5
	TRUCKS	55	11022 SB	62.2	5.2	68	69.2	92.8
	ALL VEHICLES	55	41214 SB	62.5	5.7	69	66.4	93.3
"AFTER"	CARS	55	40965 SB	62.7	5.7	69	65.1	92.3
	TRUCKS	55	8521 SB	59.8	5.7	65	70.0	83.9
	ALL VEHICLES	55	49486 SB	62.2	5.8	68	64.3	90.7
			Control Section B – Route 99 at Grant Line Road					
"BEFORE"	CARS	55	9973 SB	62.2	4.9	67	74.7	94.4
	TRUCKS	55	3373 SB	59.9	4.4	64	79.9	89.0
	ALL VEHICLES	55	13346 SB	61.6	4.9	67	74.6	93.0
"AFTER"	CARS	55	11272 SB	62.0	4.7	67	75.2	94.1
	TRUCKS	55	3445 SB	59.2	4.4	64	78.6	85.7
	ALL VEHICLES	55	14717 SB	61.3	4.8	66	74.5	92.1

TABLE 2 "Before" and "After" Speed Data for Michigan Study Sites

PERIOD	VEHICLES	SPEED LIMIT	VOLUME (ADT)	MEAN SPEED (MPH)	STND DEVN	85th % SPEED	% IN PACE	% OVER LIMIT
Test Section – Interstate 96 Near Fowlerville								
"BEFORE"	CARS	55	29861 EB	65.8	5.9	74	64.2	97.5
	TRUCKS	55	4538 EB	59.2	5.1	66	70.6	81.0
	ALL VEHICLES	55	34399 EB	64.8	6.3	73	61.0	95.2
"AFTER"	CARS	65	32698 EB	67.0	5.4	74	69.4	66.2
	TRUCKS	55	4667 EB	59.1	4.8	65	74.8	8.5
	ALL VEHICLES	55	37365 EB	65.9	5.9	73	63.8	58.5
Control Section A – Route 52 South of I-96								
"BEFORE"	CARS	55	2646 EB	61.4	7.4	70	59.3	84.1
	TRUCKS	55	411 EB	56.1	8.9	66	53.6	63.1
	ALL VEHICLES	55	3057 EB	60.6	7.9	70	57.6	81.3
"AFTER"	CARS	55	2889 EB	61.0	6.6	70	61.0	84.9
	TRUCKS	55	503 EB	55.7	6.1	63	65.1	58.3
	ALL VEHICLES	55	3392 EB	60.2	6.8	69	58.9	80.8
Control Section B – Interstate 69 Near Flint								
"BEFORE"	CARS	55	35476 EB	65.6	6.7	75	57.9	95.5
	TRUCKS	55	4237 EB	64.1	6.1	72	63.3	93.4
	ALL VEHICLES	55	39713 EB	65.5	6.7	74	58.1	95.3
"AFTER"	CARS	55	29390 EB	66.1	6.4	74	58.0	95.8
	TRUCKS	55	3891 EB	63.2	6.1	71	59.5	92.7
	ALL VEHICLES	55	33281 EB	65.8	6.4	74	57.6	95.5

TABLE 3 "Before" and "After" Speed Data for Virginia Study Sites

PERIOD	VEHICLES	SPEED LIMIT	VOLUME (ADT)	MEAN SPEED (MPH)	STND DEVN	85th % SPEED	% IN PACE	% OVER LIMIT
Test Section A – Interstate East of Marshall								
"BEFORE"	CARS	55	7117 WB	62.6	6.2	70	66.2	92.3
	TRUCKS	55	4016 WB	61.5	6.0	69	62.8	88.3
	ALL VEHICLES	55	11133 WB	62.2	6.2	70	64.7	90.8
"AFTER"	CARS	65	9002 WB	65.3	4.9	72	73.8	52.3
	TRUCKS	55	2519 WB	61.8	5.8	70	63.2	28.6
	ALL VEHICLES	65/55	11521 WB	64.5	5.3	71	68.9	47.1
Test Section B – Interstate 81 South of Lexington								
"BEFORE"	CARS	55	7843 NB	66.5	5.4	74	69.1	99.0
	TRUCKS	55	4249 NB	65.6	5.0	73	70.7	98.7
	ALL VEHICLES	55	12092 NB	66.2	5.3	73	69.7	98.9
"AFTER"	CARS	65	6620 NB	67.4	4.8	74	74.6	70.7
	TRUCKS	55	5577 NB	65.2	5.4	72	65.9	51.0
	ALL VEHICLES	65/55	12197 NB	66.4	5.2	73	70.2	61.5
Control Section A – Interstate 64 in Chesapeake								
"BEFORE"	CARS	55	19694 WB	61.2	5.8	69	65.6	93.5
	TRUCKS	55	9366 WB	58.4	5.2	68	69.2	92.8
	ALL VEHICLES	55	29060 WB	60.2	5.7	69	66.4	93.3
"AFTER"	CARS	55	20128 WB	62.7	4.0	61	65.1	92.3
	TRUCKS	55	9749 WB	59.8	3.6	63	70.0	83.9
	ALL VEHICLES	55	29887 WB	62.2	4.2	65	64.3	90.7
Control Section B – Interstate 64 in Newport News								
"BEFORE"	CARS	55	16873 EB	62.2	4.9	67	74.7	94.4
	TRUCKS	55	5009 EB	59.9	4.4	64	79.9	89.0
	ALL VEHICLES	55	21882 EB	61.6	4.9	67	74.6	93.0
"AFTER"	CARS	55	17149 EB	64.2	4.4	70	75.2	94.1
	TRUCKS	55	5830 EB	61.9	3.4	66	78.6	85.7
	ALL VEHICLES	55	22979 EB	63.5	4.2	69	74.5	92.1

TABLE 4 "Before" and "After" Speed Data for Maryland Study Site

PERIOD	VEHICLES	SPEED LIMIT	VOLUME (ADT)	MEAN SPEED (MPH)	STND DEVN	85th % SPEED	% IN PACE	% OVER LIMIT
		CONTROL SECTION – INTERSTATE 70 WEST OF FREDERICK						
"BEFORE"	CARS	55	11399 EW	65.5	5.4	73	68.3	98.3
	TRUCKS	55	3091 EW	64.4	5.8	72	68.5	96.3
	ALL VEHICLES	55	14490 EW	65.3	5.5	72	68.0	97.8
"AFTER"	CARS	55	12801 EW	65.9	5.5	73	68.1	98.5
	TRUCKS	55	2380 EB	65.5	5.5	73	67.5	97.5
	ALL VEHICLES	55	15631 EW	65.8	5.5	73	68.0	98.3

first set of study sites. The parameters of "after" speed data at sites on the routes that traverse Virginia and West Virginia are given in Table 5.

Accident Data

Accident data were collected at each site and designated as either "before" or "after" data. The "before" data covered at least 36 months preceding the effective date of the change in the speed limit, whereas the "after" data covered 12 or more months with the new speed limit. Specific information on accident characteristics was extracted from accident files, including details of vehicles involved, collision type, severity of accident, and several other variables. Volume data in terms of average daily traffic (ADT) were obtained at each site and were used to compute the accident rates that formed the basis of comparison. Three severity classifications were used: fatal (FAT), injury (INJ), and property damage only (PDO). The accidents were also classified in terms of the number of vehicles involved (i.e., one, two, or three or more). The three main categories of two-vehicle accident types were nontruck/nontruck (NT-NT), nontruck/truck (NT-T), and truck/truck (T-T). The three most common types of collisions were sideswipe, rear-end, and those with a fixed object. Tables 6 through 8 summarize the accident rates for the different locations by severity, number of vehicles, and types of vehicles and collisions.

ANALYSIS AND RESULTS

Detailed statistical comparisons were carried out to determine whether significant changes occurred in speed and accident characteristics after the implementation of a given strategy. The *T*-test was used to compare the different sets of speed data, and the chi-square and proportionality tests were used for the accident data. The following null hypotheses formed the basis for comparisons:

1. Hypothesis for "before" and "after" comparison: There is no significant difference in accident or speed characteristics between the "before" and "after" data for the sections of highway under consideration. This hypothesis was tested for changes in accident and speed characteristics at sites where the speed limit was changed from 55 to 65/55 mph and at sites where the speed limit was maintained at 55 mph. The data from a test section during the "before" period were compared with the data from the same test of control section during the "after" period. The results of this analysis also served the secondary objective of creating a background for the interpretation of the results of the accident analysis.

TABLE 5 "After" Speed Data at Virginia and West Virginia Sites

SITE	VEHICLES	SPEED LIMIT	MEAN SPEED (MPH)	SPEED VARIANCE (MPH)
ROUTE 64 (VA)	CARS	65	65.79	23.22
ROUTE 64 (VA)	TRUCKS	55	60.25	17.75
ROUTE 64 (VA)	ALL VEHICLES	65/55	64.31	27.69
ROUTE 64 (WVA)	CARS	65	65.41	11.30
ROUTE 64 (WVA)	TRUCKS	65	61.94	8.74
ROUTE 64 (WVA)	ALL VEHICLES	65	64.36	13.13
ROUTE 81 (VA)	CARS	65	66.02	12.43
ROUTE 81 (VA)	TRUCKS	55	59.78	12.25
ROUTE 81 (VA)	ALL VEHICLES	65/55	63.05	24.60
ROUTE 81 (WVA)	CARS	65	66.18	16.06
ROUTE 81 (WVA)	TRUCKS	65	64.23	19.58
ROUTE 81 (WVA)	ALL VEHICLES	65	65.26	18.54
ROUTE 77 (VA)	CARS	65	66.77	19.11
ROUTE 77 (VA)	TRUCKS	55	58.42	15.56
ROUTE 77 (VA)	ALL VEHICLES	65/55	64.30	32.48
ROUTE 77 (WVA)	CARS	65	63.84	19.54
ROUTE 77 (WVA)	TRUCKS	65	57.78	16.93
ROUTE 77 (WVA)	ALL VEHICLES	65	62.02	26.40

TABLE 6 Accident Rates at First Set of Study Sites (California and Michigan)

Site	Period	Time (yr)	Route	Severity Fat	Injury	PDO	Number of Vehicles 1	2	3+	Two-Vehicle Accidents NT–NT	NT–T	T–T	Types of Collision SDSWP	Rearend
CALIFORNIA SITES														
TEST	"BEFORE"	3.0	5	0.73	16.96	38.61	40.57	15.0	0.73	10.09	3.93	0.98	3.44	6.14
	"AFTER"	1.75	5	0.63	18.02	30.68	32.57	15.81	0.94	12.66	2.84	0.31	6.64	5.06
CONT A	"BEFORE"	3.0	5	0.46	11.15	12.56	8.94	12.36	2.87	10.44	1.53	0.39	5.28	5.81
	"AFTER"	1.75	5	0.55	12.47	16.45	10.04	15.33	4.05	13.45	1.42	0.46	6.72	7.41
CONT B	"BEFORE"	3.0	99	1.31	45.30	60.77	50.52	47.91	8.76	41.58	5.03	1.30	9.51	29.45
	"AFTER"	1.75	99	1.66	50.52	58.30	48.57	49.13	12.77	44.97	3.33	0.83	12.49	32.20
MICHIGAN SITES														
TEST	"BEFORE"	3.0	96	0.42	7.98	28.80	24.46	10.53	2.21	6.96	2.55	1.02	0.34	10.60
	"AFTER"	1.0	96	0.23	11.34	45.12	36.61	17.01	3.07	11.82	4.01	1.18	0.05	12.99
CONT A	"BEFORE"	3.0	52	0.00	23.01	110.49	93.19	32.21	8.05	20.71	9.20	2.30	0.02	4.63
	"AFTER"	1.0	52	3.06	24.53	141.06	119.58	36.79	12.26	18.40	15.33	3.06	0.01	3.07
CONT B	"BEFORE"	3.0	69	0.17	20.66	53.74	39.81	30.35	4.41	22.75	5.63	1.97	0.52	30.23
	"AFTER"	1.0	69	0.21	30.45	69.67	60.70	32.53	7.09	20.02	8.55	3.96	0.42	41.51

*Accidents per 100 million vehicle miles of travel.
NT–NT = non-truck/non-truck, NT–T = non-truck/truck, T–T = truck/truck, and SDSWP = sideswipe.

2. Hypothesis for test and control comparison: There is no significant difference in speeds and accidents between the sites where the 65/55-mph limit is in effect and the sites where the 55-mph limit has been maintained. This hypothesis tested for any spillover effects of speed limit change in the test area. For example, drivers exiting a test section may continue to driver at higher speeds as a result of speed adaptation and affect the accident characteristics at locations with 55-mph speed limit.

3. Hypothesis for 65/65 and 65/55 comparison: There is no significant difference in speed and accident characteristics between sites having 65/65-mph speed limit and those with 65/55-mph speed limit. This hypothesis tested for the differences in the effect of 65/65- and 65/55-mph speed limits on accident characteristics at similar highway sections. The main purpose of the speed comparison was to investigate the effect on vehicle speeds of the imposition of a DSL.

The following categories of vehicle speeds were analyzed: average speed and 85th percentile speed of passenger cars, average speed and 85th percentile speed of large trucks, and average speed and 85th percentile speed of all vehicles.

In addition, the effect of the DSL on speed dispersion and on the difference between mean speeds of cars and trucks was evaluated. Speed dispersion is defined as the measured difference between average speed and 85th percentile speed. This parameter is sensitive to groups of excessive speeders, which are not totally reflected by average speed.

TABLE 7 Accident Rates at First Set of Study Sites (Virginia and Maryland)

Site	Period	Route	Severity Fat	Injury	PDO	Number of Vehicles 1	2	3+	Two-Vehicle Accidents NT–NT	NT–T	T–T	Types of Collision SDSWP	Rearend	FIXOBJ
VIRGINIA SITES														
TEST A	"BEFORE"	66	0.50	12.87	26.25	10.09	23.22	6.31	17.93	3.78	1.51	4.54	5.04	17.16
	"AFTER"	66	1.42	28.55	31.42	19.99	33.55	7.85	26.43	5.71	1.42	5.71	5.71	32.83
TEST B	"BEFORE"	81	0.93	21.82	29.86	19.14	21.82	4.95	11.79	7.22	2.81	7.89	7.22	27.57
	"AFTER"	81	0.76	24.94	38.77	27.24	30.31	6.91	16.12	10.74	3.45	9.97	10.36	39.52
CONT A	"BEFORE"	64	0.00	46.47	35.91	35.91	38.02	8.45	25.35	8.45	4.22	2.11	6.33	14.78
	"AFTER"	64	0.00	31.14	52.95	35.82	37.37	10.90	21.80	10.90	4.67	1.55	6.22	14.01
CONT B	"BEFORE"	64	1.75	45.61	49.12	47.36	29.82	19.29	19.30	8.77	1.75	1.75	3.51	15.78
	"AFTER"	64	0.00	53.04	68.81	24.37	65.94	31.54	53.04	12.90	0.00	4.30	10.03	20.07
MARYLAND SITE														
CONT	"BEFORE"	70	1.21	35.10	28.62	36.52	20.08	8.32	16.63	2.84	0.61	4.54	5.04	
	"AFTER"	70	0.75	21.44	37.62	37.63	20.31	1.88	16.56	3.00	0.75	5.71	5.64	

*Accidents per 100 million vehicle miles of travel.
NT–NT = non-truck/non-truck, NT–T = non-truck/truck, T–T = truck/truck, SDSWP = sideswipe, and FIXOBJ = fixed object.

TABLE 8 Accident Rates in Virginia and West Virginia for the Second Set of Study Sites

ROUTE	DAILY TRAFFIC CATEGORY	SEVERITY FAT	INJ	ALL	NO. OF VEHICLES 1	2	3+	TWO-VEHICLE ACCIDENTS NT–NT	NT–T	T–T	TYPES OF COLLISION SS	RE	FO
ACCIDENTS IN VIRGINIA DURING "BEFORE" PERIOD													
64	< 50000	1.055	27.81	71.14	42.96	22.61	5.81	13.34	4.60	0.68	12.71	17.46	25.42
	> 50000	0.701	54.48	141.81	35.55	68.90	37.45	57.68	10.41	0.90	24.11	48.23	69.17
77	< 50000	0.897	27.36	60.99	34.98	23.32	3.14	4.93	7.63	3.59	5.12	22.15	30.19
81	< 50000	0.971	23.32	56.84	34.29	20.94	1.75	5.54	10.15	1.26	7.19	19.27	28.18
ACCIDENTS IN WEST VIRGINIA DURING "BEFORE" PERIOD													
64	< 50000	1.110	39.60	116.32	62.81	47.69	5.82	30.04	14.78	2.86	17.45	24.43	31.41
77	< 50000	0.730	18.31	55.49	29.96	22.75	2.77	14.33	7.05	1.36	8.32	11.65	14.98
81	< 50000	0.330	13.88	38.99	21.05	15.98	1.95	10.07	4.95	0.96	5.85	8.19	10.53
ACCIDENTS IN VIRGINIA DURING "AFTER" PERIOD													
64	< 50000	0.918	24.94	64.35	39.98	20.55	4.09	10.52	4.37	0.35	15.11	18.31	29.52
	> 50000	0.607	41.57	126.23	28.12	67.03	31.38	49.39	8.66	0.68	21.06	39.41	63.98
77	< 50000	0.675	19.56	57.66	35.74	20.23	1.68	5.06	6.41	1.01	4.36	23.14	29.85
81	< 50000	1.143	20.29	51.35	28.86	19.43	3.18	5.22	7.92	1.22	8.47	17.22	24.81
ACCIDENTS IN WEST VIRGINIA DURING "AFTER" PERIOD													
64	< 50000	1.480	30.81	78.21	45.36	29.72	3.13	19.32	8.32	2.08	10.95	15.64	21.12
77	< 50000	0.734	35.64	71.82	41.65	27.29	2.87	17.73	7.63	1.91	10.05	14.36	19.39
81	< 50000	1.310	19.62	52.00	30.16	19.76	2.08	12.84	5.53	1.38	7.28	10.40	14.04

NT–NT = non-truck/non-truck, NT–T = non-truck/truck, T–T = truck/truck, SS = sideswipe, RE = rear-end, and FO = fixed object.

Mean Speeds

Table 9 gives the values of the test statistic computed for comparisons of mean speeds. It is clear that mean speeds of passenger cars have increased as a result of the increase in the maximum speed limit for passenger cars; thus, Null Hypothesis 1 for speeds can be rejected. However, this increase is fewer than 3 mph at all sites in response to an increase of 10 mph in the speed limit (see Table 1). Only one control site in Michigan showed significant change; however, the actual difference between the "before" and "after" speeds at this site was only 0.6 mph (see Table 4). These sites therefore seem to be good choices for control areas in the accident analysis. Hence, it can be concluded that the control sections were not significantly affected by spillover effects from the test areas and that Null Hypothesis 1 can be accepted with regard to speeds for the control sites.

At the test sites where a differential speed limit was imposed, the difference between mean speeds of nontrucks and trucks showed a dramatic increase after the imposition of the differential speed limit. This was manifested in more conflicts between these types of vehicles.

Speed Dispersion

The analysis also showed that speed dispersion decreased at all of the test sites at which the DSL was imposed except for the California site. The increase in the average speeds of passenger cars as a result of the institution of a DSL has partially masked the effect of excessive speeding prevalent during the "before" period. The net effect was a reduction in speed dispersion. However, as the proportion of trucks (subject to the 55-mph limit) in the traffic stream increases, a DSL can cause a significant increase in speed dispersion and consequently in interaction among different vehicles.

Accident Data Comparison

As in the speed data analysis, Null Hypotheses 1 and 2 were tested for the accident data comparison. To better understand which characteristic of accidents is considerably affected, various categories of accidents were studied.

"Before" and "After" Comparison at Test Sites

In the "before" and "after" comparison, the accident data from test sections obtained during the "before" period were compared with the corresponding data from the same section during the "after" period. To test for significant changes in different categories of accidents, chi-square tests with two degrees of freedom were conducted and compared with the critical value (i.e., $X^2_{2,\,0.05} = 5.99$). None of the comparisons indicated significant change; therefore, it can be concluded that the increase in speed limit did not significantly affect the accident rates at the test sections and that Null Hypothesis 1

TABLE 9 Results of Mean Speed Data Analysis

Site		T-statistic of Mean Speeds	
	Passenger Cars	Trucks	All Vehicles
		CALIFORNIA	
Test	9.13*	-9.31	4.62*
Control A	0.00	-30.31	-7.82
Control B	-3.03	-6.56	-5.17
		MICHIGAN	
Test	26.45*	-0.97	24.08*
Control A	-2.11	-0.77	-2.16
Control B	9.69*	-6.64	6.17*
		VIRGINIA	
Test A	30.05*	2.01*	29.96*
Test B	10.61*	-3.79	2.96*
Control A	0.39	-1.61	-1.42
Control B	-4.27	-2.11	0.09
		MARYLAND	
Control	0.57	0.74	0.98

* significant at 5% confidence level

for accidents can be accepted. However, some increases in the rates of most collisions were observed, although these increases were not significant at the 5 percent level (see Tables 6 through 8). Similar results were obtained for the control sites.

Test and Control Comparison

In this comparison, accident data from test sections were compared with data from each control section. A computer program for chi-square analysis (which takes both "before" and "after" accident rates into consideration) was used, but with the critical value being $X^2_{1,\ 0.05} = 3.84$. Table 10 gives the chi-square results of comparison between test and control sites for the different accident characteristics. Almost all of the comparisons were insignificant, indicating that there is no significant change in accident rates at test and control sites. In other words, the increase in speed limits had no significant effect on accident rates at the test and control sites. Therefore, Null Hypothesis 2 for accidents can be accepted.

Comparison of 65/65- and 65/55-mph Speed Limits

Three states adjacent to Virginia have a uniform 65-mph speed limit: Kentucky, West Virginia, and North Carolina. Unfortunately, accident and speed data from only West Virginia could be obtained for this study. The comparison was therefore done only for West Virginia and Virginia. Table 5 gives the mean speed and speed variances observed on the selected routes after the change in speed limits. The data indicate that the average speeds of trucks also increased as a result of the uniform increase to 65 mph in West Virginia. Compared with speed variance in Virginia, where a DSL exists, the overall speed variances were lower in West Virginia, where a uniform maximum speed limit (65/65 mph) exists.

Various types of accident rates on West Virginia rural Interstate routes after the increase in the speed limit were also compared with those in Virginia. For direct comparison, only routes that traverse both Virginia and West Virginia were considered. Also, the influence of traffic volume was isolated by segregating accidents on highway sections carrying different levels of average daily traffic. Table 8 gives the various

TABLE 10 Chi-Square Results of Test/Control Comparisons for the First Set of Study Sites

SITES		SEVERITY		NO. OF VEHICLES			TWO-VEHICLE ACCIDENTS			TYPES OF COLLISION		
COMPARED	FAT	INJ	PDO	1	2	3+	NT–NT	NT–T	T–T	SS	RE	FO
T - CA	0.033	0.009	1.265	0.426	0.099	0.073	0.010	0.050	0.238	0.267	0.330	1.726
T - CB	0.035	0.016	0.386	0.340	0.011	0.022	0.103	0.054	0.091	0.287	0.194	2.495
					MICHIGAN							
T - CA	0.082	0.297	0.575	0.274	0.578	0.013	1.295	0.036	0.027	0.027	0.539	0.429
T - CB	0.190	0.013	0.432	0.004	0.790	0.058	1.370	0.004	0.447	0.511	0.067	0.931
					VIRGINIA							
T1 - CA	0.087	8.964*	0.374	2.335	1.183	0.026	1.632	0.041	0.070	0.231	0.036	2.223
T1 - CB	0.162	2.764	0.237	9.087*	1.498	0.213	2.399	0.016	0.971	0.392	1.203	0.852
T2 - CA	1.421	2.057	0.158	0.876	0.917	0.018	0.931	0.064	0.010	0.222	0.274	0.860
T2 - CB	0.268	0.004	0.068	7.013	1.718	0.060	2.283	0.039	1.474	0.470	0.830	0.084

*Denotes significant difference at the 5 percent confidence level.
NT–NT = non-truck/non-truck, NT–T = non-truck/truck, T–T = truck/truck, SS = sideswipe, RE = rear-end, and FO = fixed object.

TABLE 11 Comparison of Accident Rates Between Virginia and West Virginia for the Second Set of Study Sites

SEVERITY			NO. OF VEHICLES			TWO-VEHICLE ACCIDENTS			TYPES OF COLLISION		
FAT	INJ	ALL	1	2	3+	NT–NT	NT–T	T–T	SS	RE	FO
VIRGINIA: BEFORE/AFTER COMPARISON											
0.44	2.07	0.92	0.60	2.85*	0.42	0.31	0.64	1.06	0.25	0.03	0.06
WEST VIRGINIA: BEFORE/AFTER COMPARISON											
1.42	0.51	0.12	0.08	0.32	0.67	0.24	0.57	0.10	0.30	0.25	0.12
BEFORE PERIOD: VIRGINIA/WEST VIRGINIA COMPARISON											
1.09	0.28	0.30	0.04	0.67	0.03	1.54	0.43	0.11	0.52	0.95	1.38
AFTER PERIOD: VIRGINIA/WEST VIRGINIA COMPARISON											
1.00	1.41	1.09	0.75	1.83	0.38	3.66*	0.70	2.76	0.03	2.53	3.68*

*Denotes significant difference at the 5 percent confidence level.
NT–NT = non-truck/non-truck, NT–T = non-truck/truck, T–T = truck/truck, SS = sideswipe, RE = rear-end, and FO = fixed object.

types of accident rates observed during the "before" and "after" periods in both states. The accident rates corresponding to "before" and "after" conditions and between states were statistically compared by category. The *t*-values obtained were compared against the critical value $t_{4,\,0.05} = 2.77$ to identify significant differences in the effect of the two types of speed limits.

The results indicate that there were no significant differences in the overall accident rates between the "before" and "after" periods in each state. This was also true for fatal and injury accidents. These results are similar to the results presented earlier for Michigan, California, and other sites in Virginia. This reinforces the conclusion that although increasing the speed limit to 65 mph for passenger cars may have resulted in an increase in the number of fatalities, it has not resulted in a significant increase in fatal, injury, or overall accident rates. Therefore, Null Hypothesis 3 can be accepted. However, there was a significant increase in two-vehicle accident rates in Virginia, which supports the premise that a DSL results in increased interaction among vehicles in the traffic stream.

A comparison between the "after" data for Virginia and West Virginia gives an indication of the difference in the effect on accident characteristics of the two speed strategies. Table 11 indicates that there was no significant difference between the two states in fatal, injury, or overall accident rates. This strongly indicates that the DSL does not have any safety benefit over the uniform speed limit. This confirms the results of a previous study by Garber and Gadiraju (*2*) that used simulation techniques to investigate the effect of DSL strategies.

SUMMARY OF FINDINGS

- The increase in the speed limit for passenger cars on rural Interstate highways has resulted in an increase in the mean speeds of passenger cars on these highways.
- The mean speed of passenger cars increased from a range of 61 to 64 mph to a range of 62 to 67 mph, resulting in an increase in mean speed of from 1 to about 3 mph compared with the 10-mph increase in the posted speed limit (because the average speeds for passenger cars were much higher than 55 mph during the period of the 55-mph speed limit).
- Where the speed limit of trucks was maintained at 55 mph, no significant difference in their mean speed was observed.
- Speed variance for passenger cars decreased with the increase in the speed limit to 65 mph.
- Speed dispersion also decreased somewhat because of the increase in speed limit for passenger cars.
- The increase in the posted speed limit to 65 mph on rural Interstate highways has not resulted in a significant increase in accident rates.
- There were no spillover effects of the increase in speed limit; that is, the speed and accident characteristics at control sites were not affected.
- The DSL (65/55 mph) has no significant effect in reducing (*a*) nontruck/truck accident rates or (*b*) two-vehicle accident rates, compared with the uniform speed limit (65/65 mph). There is, however, some indication that the DSL may increase the rates of some types of accidents such as two-vehicle accidents, although this increase is not significant at the 5 percent significance level.

CONCLUSIONS

- The increase in the maximum speed limit to 65 mph for passenger cars at the sites tested did not result in a significant increase in fatal, injury, or overall accident rates.
- The increase in the maximum speed limit to 65 mph for passenger cars at the sites tested did not result in a significant increase in the mean speed of trucks.
- The DSL (65/55 mph) is not more effective than the uniform speed limit (65/65 mph) in reducing the safety of an increased maximum speed limit.
- The differential speed limit increases the interaction among vehicles in a traffic stream as a result of the increase in speed variance.
- The imposition of the differential speed limit on Interstate highways with AADT less than 50,000 may result in higher rates for certain types of accidents such as rear-end and side-

swipe accidents, although the increase is not significant at the 5 percent significance level.

ACKNOWLEDGMENTS

This study was conducted under the sponsorship of AAA Foundation for Traffic Safety, Washington, D.C. The authors gratefully acknowledge the sponsor's cooperation and assistance. The authors also acknowledge the assistance rendered by Martin R. Parker of Martin R. Parker & Associates, Michigan, for his help in providing some of the necessary data. Thanks are also due to others who provided accident data from Virginia and West Virginia.

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Publication of this paper sponsored by Committee on Traffic Law Enforcement.

Effects of the 65-mph Speed Limit on Traffic Accidents in Ohio

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The effects of the 65-mph speed limit on traffic accidents on rural Interstate highways posted at 65 or 55 mph and rural non-Interstate highways posted at 55 mph in Ohio were examined by analyzing the accident data for 36 months before the implementation of the speed change law and an equal number of months after the implementation. The changes in accident rates, that is, the average number of accidents per month, were examined relative to weather conditions and seasons as well as day of week, time of day, light conditions, and vehicle mix. It was found that fatal accident rates on rural Interstate highways posted at 65 mph or rural non-Interstate highways posted at 55 mph had not significantly changed after the implementation of the 65-mph speed limit. Fatal accident rates on rural Interstate highways posted at 55 mph showed an increase in the "after" period. However, when the data were categorized according to weather conditions, no significant change in fatal accident rates was found. There have been some increases in injury and property damage only (PDO) accident rates on rural Interstate highways posted at 65 mph. The injury and PDO accident rates on rural Interstate highways posted at 55 mph have decreased and shown no indication of adverse "spillover" effect. Injury and PDO accidents as well as the severity of accidents have decreased on the non-Interstate highways posted at 55 mph, perhaps indicating positive effects of the seat belt law, speed enforcement, and geometric and operational improvements in recent years.

In July 1987, the state of Ohio changed the speed limit on rural Interstate highways from 55 to 65 mph. Since then, efforts have been made to understand the impacts of the change in speed limit on vehicle operating speed, accident distributions, and the safety of motorists on the highways. In previous years, several other states with Interstate speed limit of 65 mph have performed studies on accident distributions in their respective states. The results of these studies are sometimes different, and even conflicting, among the states. Hence a study that considers the unique characteristics of highways, traffic, and weather conditions in Ohio would allow us to better understand the changes that have occurred in the state since the speed limit on rural Interstate highways was changed to 65 mph.

The objective of this study was to evaluate the impacts of the 65-mph speed limit on accident distributions in Ohio. In particular, the effects of the 65-mph speed limit were examined for the following categories of highways:

1. Rural Interstate highways posted at 65 mph (rural was defined as areas outside corporation limits),
2. Rural Interstate highways posted at 55 mph, and
3. Rural non-Interstate highways posted at 55 mph.

The last two categories were included in the study to determine whether there was any "spillover" effect of the 65-mph speed limit on Interstate and non-Interstate highways with 55-mph speed limit.

RESEARCH APPROACH

The Ohio Department of Highway Safety (ODHS) provided access to the accident data existing in the mainframe computer, which was remotely and selectively downloaded to a personal computer for each month of the study periods. The list of Interstate highway segments along with the posted speed and log points in each county was provided by ODHS. Although accident analyses are generally performed by using control or comparison sites, the possibility of defining such sites when the treatment (the law change) is implemented at one point in time does not exist. Hence any analysis that is performed to examine the effects of the Interstate 65-mph speed limit must control for the effects of external factors that are acting on accident distributions at the same time.

"Before" and "After" Periods

The Interstate 65-mph speed limit went into effect on July 15, 1987. Two periods consisting of 36 months before July 1987 and an equal number of months after July 1987 were used in the analysis of the accident data. The month of July 1987 was excluded from the study. The two periods were (*a*) "before" (July 1984 to June 1987) and (*b*) "after" (August 1987 to July 1990).

Type of Accidents

Accident frequency was used as the criterion for evaluation. The following types of accidents were included: fatal, injury, and property damage only (PDO) accidents. Injury accidents were further subdivided into the following categories: serious visible injury, minor visible injury, and no visible injury.

Vehicles Miles Traveled

A list of daily vehicle miles traveled (VMT) for rural Interstate highways posted at 65 and 55 mph and rural non-Interstate

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highways for each year was obtained from the Ohio Department of Transportation. Using 1985 as the base year, the accident frequency for each month was adjusted for change in VMT in that month. Thus the accident frequency for 1985 was kept constant and the frequencies for the remaining years were adjusted in proportion to the change in VMT relative to 1985.

Weather

When the time series plots of the monthly accident data for 6 years were examined, they clearly exhibited the effects of adverse weather conditions and seasons. It seemed that any attempt to analyze the accident data without filtering the effects of weather would not be meaningful. Hence the data were further subdivided into two categories: accidents under normal weather conditions and accidents under adverse weather conditions. The analysis is based on weather conditions that existed at the time and place of accidents during the study periods. The results cannot necessarily be extrapolated into future years because of the changing nature of weather conditions.

Seasons

After the data were categorized into the two groups according to weather conditions, they were divided into four quarters as follows: Quarter 1, January to March; Quarter 2, April to June; Quarter 3, July to September; and Quarter 4, October to December. The quarterly accident data were separately analyzed.

Other Factors

The effects of the following variables on accident rates were also examined:

- Day of week: The days were divided into weekdays and weekends.
- Time of day: The time of day was divided into 6:00 a.m.–6:00 p.m. and 6:00 p.m.–6:00 a.m.
- Light conditions: The light condition was divided into daylight and dark.
- Vehicle mix: The first two vehicles in the accidents were examined by dividing the vehicles into two subcategories: light vehicles (e.g., car and pickup truck) and heavy vehicles (e.g., straight truck, truck-trailer, bus, and recreational vehicles).

Hypothesis Testing

After adjusting the data into several categories and subcategories as described, the accident data were analyzed by using the STATGRAPHICS statistical package (*1*). The Comparison of Poisson Rates procedure was used to compare the mean rate of accidents (that is, the average number of accidents per month) for the 36 months of the "before" and "after" periods. For the quarterly data, the analysis was performed for 9 months in each period. The standardized test statistic z for equal rates was calculated to test the hypothesis that the accident rates during the "before" and "after" periods are the same. Finally, a probability level based on a large sample approximation was computed. The test was performed at the 0.05 level of significance. The results of the analysis that were found significant are discussed in the following sections.

RURAL INTERSTATE HIGHWAYS POSTED AT 65 mph

The results of the accident analysis for rural Interstate highways posted at 65 mph are described below (see Tables 1 to 3). The mean accident rates refer to the average number of accidents per month, after adjusting for the changes in VMT as described previously.

When the fatal accident data for the two periods before and after the implementation of the Interstate 65-mph speed limit were examined, the mean fatality rates were not significantly different in the two periods. The analysis showed that the 65-mph speed limit had not adversely affected the mean fatal accident rates on Interstate highways posted at 65 mph.

The mean accident rates for injury and PDO accidents were found to be significantly different in the "before" and "after" periods. They indicated that the Interstate 65-mph speed limit had increased injury accidents by 16 percent and PDO accidents by 10 percent. When the data were classified according to weather conditions, injury accidents increased by 12 and 23 percent for normal and adverse weather conditions, respectively, and the PDO accidents increased by 10 and 8 percent, respectively. A further analysis of the data by quarter showed that the increases in injury and PDO accident rates were limited to Quarters 3 and 4, indicating seasonal effects of the change in the speed limit.

No differences were found among the mean serious visible injury accident rates in the two periods. However, minor visible injury and no visible injury accidents increased by 6 and 28 percent, respectively. When classified according to weather conditions, the mean rates for minor visible injury accidents showed no significant difference between the two periods. The no visible injury accidents increased by 22 and 40 percent for normal and adverse weather conditions, respectively. "No visible injury" accidents are those claimed by individuals but unable to be verified by the reporting officers. Overall, the analysis showed that the increase in mean accident rates after the implementation of the 65-mph speed limit was mostly limited to injury and PDO accidents.

Mean fatal accident rates experienced no changes during weekdays or weekends under normal and adverse weather conditions. Injury accidents under normal weather conditions increased by 8 percent during weekdays and 21 percent during weekends. Fatal accident rates between 6:00 a.m. and 6:00 p.m. and between 6:00 p.m. and 6:00 a.m. did not experience any change after the implementation of the 65-mph speed limit. However, serious visible injury accidents between 6:00 a.m. and 6:00 p.m. increased by 15 to 33 percent. (The two percentages represent accidents for normal and adverse weather conditions.) Minor visible injury accidents between 6:00 p.m. and 6:00 a.m. increased by 9 percent under normal weather

TABLE 1. Accident Frequency and Results of Significance Test—Interstate Highways Posted at 65 mph

		Fatal[a]	Injury[b]	PDO[c]	Type2[d]	Type3[e]	Type4[f]
3 Years	Before	98	3536	11058	395	2025	1714
	After	109	4097	12156	426	2158	2199
		NS[g]	S[h]	S[h]	NS[g]	S[h]	S[h]
Quarter 1	Before	24	975	3074	79	535	508
	After	23	1012	2894	96	493	590
		NS[g]	S[h]	S[h]	NS[g]	S[h]	S[h]
Quarter 2	Before	34	799	2668	111	460	361
	After	26	802	2670	96	442	397
		NS[g]	NS[g]	NS[g]	NS[g]	NS[g]	NS[g]
Quarter 3	Before	26	842	2056	109	535	367
	After	36	1023	2379	117	609	495
		NS[g]	S[h]	S[h]	NS[g]	S[h]	S[h]
Quarter 4	Before	14	920	3258	95	494	478
	After	24	1261	4212	117	613	718
		NS[g]	S[h]	S[h]	NS[g]	S[h]	S[h]

[a] Fatal accidents
[b] Injury accidents
[c] Property damage only accidents
[d] Serious visible injury
[e] Minor visible injury
[f] No visible injury
[g] Not significant at 0.05 level of significance
[h] Significant at 0.05 level of significance

TABLE 2 Accident Frequency by Weather Conditions and Results of Significance Test—Interstate Highways Posted at 65 mph

		Fatal[a]		Injury[b]		PDO[c]	
		Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]
3 Years	Before	80	18	2379	1157	7652	3406
	After	79	30	2672	1425	8463	3693
		NS[f]	NS[f]	S[g]	S[g]	S[g]	S[g]
Quarter 1	Before	20	4	437	538	1461	1613
	After	14	9	430	582	1383	1511
		NS[f]	NS[f]	NS[f]	NS[f]	NS[f]	NS[f]
Quarter 2	Before	26	8	646	153	2202	466
	After	21	5	667	135	2257	413
		NS[f]	NS[f]	NS[f]	NS[f]	NS[f]	NS[f]
Quarter 3	Before	23	3	732	110	1813	243
	After	29	7	845	178	2063	316
		NS[f]	NS[f]	S[g]	S[g]	S[g]	S[g]
Quarter 4	Before	11	3	563	357	2175	1083
	After	15	9	730	531	2759	1453
		NS[f]	NS[f]	S[g]	S[g]	S[g]	S[g]

[a] Fatal accidents
[b] Injury accidents
[c] Property damage only accidents
[d] Normal weather
[e] Adverse weather
[f] Not significant at 0.05 level of significance
[g] Significant at 0.05 level of significance

TABLE 3 Injury Accident Frequency by Weather Conditions and Results of Significance Test—Interstate Highways Posted at 65 mph

		Type2 Injury[a]		Type3 Injury[b]		Type4 Injury[c]	
		Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]
3 Years	Before	301	94	1419	606	1078	636
	After	318	108	1492	666	1311	888
		NS[f]	NS[f]	NS[f]	NS[f]	S[g]	S[g]
Quarter 1	Before	43	36	252	283	208	300
	After	51	45	236	257	212	378
		NS[f]	NS[f]	NS[f]	NS[f]	NS[f]	S[g]
Quarter 2	Before	97	14	375	85	282	79
	After	84	12	372	70	319	78
		NS[f]	NS[g]	NS[f]	NS[f]	NS[f]	NS[f]
Quarter 3	Before	96	13	465	70	320	47
	After	108	9	513	96	394	101
		NS[f]	NS[f]	NS[f]	S[g]	S[g]	S[g]
Quarter 4	Before	64	31	326	168	268	210
	After	75	42	370	243	386	332
		NS[f]	NS[f]	NS[f]	S[g]	S[g]	S[g]

[a] Serious visible injury
[b] Minor visible injury
[c] No visible injury
[d] Normal weather
[e] Adverse weather
[f] Not significant at 0.05 level of significance
[g] Significant at 0.05 level of significance

conditions. Mean fatal accident rates experienced no change during daylight or dark conditions. Injury accidents in daylight conditions increased by 13 to 35 percent. PDO accidents under dark and normal weather conditions increased by 16 percent. Finally, accidents involving only light vehicles increased by 34 to 45 percent. Mean accident rates involving light and heavy vehicles were not different.

RURAL INTERSTATE HIGHWAYS POSTED AT 55 mph

The results of the analysis of accidents on rural Interstate highways posted at 55 mph (existing outside corporation lines) are described below (see Tables 4 to 6).

When fatal accident data for the two periods before and after the implementation of the Interstate 65-mph speed limit were examined, the mean fatality rates were found to be significantly different at the 0.06 level of significance. Accident frequency had increased from 53 in the "before" period to 75 in the "after" period (an increase of 41 percent). However, when the accident data were categorized by normal and adverse weather conditions, no significant difference in the mean accident rates was found. The only significant difference in mean fatal accident rates occurred under normal weather conditions during Quarter 1. (The number of accidents increased threefold, from 5 to 15, during Quarter 1.) No significant differences in fatal accident rates were found during the remaining three quarters.

The analysis showed that injury and PDO accidents decreased by 5 and 3 percent, respectively. Serious visible injury accidents decreased by 23 percent, and minor visible accidents decreased by 15 percent. There was no significant difference between the "no visible injury" accident rates in the two periods. An exception was the mean PDO accident rate during adverse weather conditions, which showed a decrease of 12 percent in the "after" period.

The data were further analyzed according to injury severity under normal and adverse weather conditions. Serious visible injury accidents under normal weather conditions decreased by 27 percent, with no difference in accident rates under adverse weather conditions. In addition, minor visible injury accidents under normal and adverse weather conditions decreased by 15 percent. Although the decreases in accidents cannot be directly related to the Interstate 65-mph speed limit, perhaps they can be attributed to other factors such as seat belt law, speed enforcement, and so forth. When the data were further analyzed by quarter, it was found that the majority of the reductions in injury rates occurred under normal weather conditions.

Mean fatal accident rates were not significantly different during weekdays or weekends under normal and adverse weather conditions. However, fatal accidents between 6:00 a.m. and 6:00 p.m. under normal weather conditions increased by 123 percent, from 13 to 29. Whereas the increase in accident rates could, at least partially, be attributed to the Interstate 65-mph speed limit, the effects of other factors such as heavy traffic volumes during these hours should be considered. Serious visible injury accidents between 6:00 p.m. and 6:00 a.m. decreased by 9 to 12 percent. Fatal accidents under daylight and normal weather conditions increased from 15 to 30, an increase of 100 percent. The number of accidents

TABLE 4 Accident Frequency and Results of Significance Test—Interstate Highways Posted at 55 mph

		Fatal[a]	Injury[b]	PDO[c]	Type2[d]	Type3[e]	Type4[f]
3 Years	Before	53	4312	9600	423	2021	2460
	After	75	4094	9257	326	1721	2582
		S[i]	S[h]	S[h]	S[h]	S[h]	NS[g]
Quarter 1	Before	7	1049	2652	91	450	615
	After	19	971	2253	60	381	636
		S[h]	NS[g]	S[h]	S[h]	S[h]	NS[g]
Quarter 2	Before	19	983	2112	113	481	544
	After	24	932	2154	91	406	575
		NS[g]	NS[g]	NS[g]	NS[g]	S[h]	NS[g]
Quarter 3	Before	15	1134	2120	121	556	627
	After	13	1009	2126	89	444	615
		NS[g]	S[h]	NS[g]	S[h]	S[h]	NS[g]
Quarter 4	Before	13	1148	2717	99	535	673
	After	20	1181	2724	86	491	755
		NS[g]	NS[g]	NS[g]	NS[g]	NS[g]	S[h]

[a] Fatal accidents

[b] Injury accidents

[c] Property damage only accidents

[d] Serious visible injury

[e] Minor visible injury

[f] No visible injury

[g] Not significant at 0.05 level of significance

[h] Significant at 0.05 level of significance

[i] Significant at 0.06 level of significance

TABLE 5 Accident Frequency by Weather Conditions and Results of Significance Test—Interstate Highways Posted at 55 mph

		Fatal[a]		Injury[b]		PDO[c]	
		Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]
3 Years	Before	45	8	3056	1256	6721	2879
	After	61	14	2926	1168	6737	2520
		NS[f]	NS[f]	NS[f]	NS[f]	NS[f]	S[g]
Quarter 1	Before	5	2	566	483	1341	1311
	After	15	4	579	392	1283	970
		S[g]	NS[f]	NS[f]	NS[f]	S[g]	S[g]
Quarter 2	Before	17	2	817	166	1744	368
	After	21	3	744	188	1759	395
		NS[f]	NS[f]	NS[f]	NS[f]	NS[f]	NS[f]
Quarter 3	Before	13	2	976	158	1851	269
	After	12	1	838	171	1845	281
		NS[f]	S[g]	NS[f]	NS[f]	NS[f]	NS[f]
Quarter 4	Before	11	2	698	450	1786	931
	After	14	6	764	417	1850	874
		NS[f]	NS[f]	NS[f]	NS[f]	NS[f]	NS[f]

[a] Fatal accidents

[b] Injury accidents

[c] Property damage only accidents

[d] Normal weather

[e] Adverse weather

[f] Not significant at 0.05 level of significance

[g] Significant at 0.05 level of significance

TABLE 6 Injury Accident Frequency and Results of Significance Test—Interstate Highways Posted at 55 mph

		Type2 Injury[a]		Type3 Injury[b]		Type4 Injury[c]	
		Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]
3 Years	Before	348	75	1454	567	1704	756
	After	254	72	1244	477	1822	760
		S[g]	NS[f]	S[g]	S[g]	S[g]	NS[f]
Quarter 1	Before	56	35	251	199	320	295
	After	42	18	240	141	358	278
		NS[f]	S[g]	NS[f]	S[g]	NS[f]	NS[f]
Quarter 2	Before	101	12	397	84	442	102
	After	73	18	325	81	459	116
		S[g]	NS[f]	S[g]	NS[f]	NS[f]	NS[f]
Quarter 3	Before	114	7	484	72	530	97
	After	78	11	370	74	509	106
		NS[f]	NS[f]	NS[f]	S[g]	S[g]	S[g]
Quarter 4	Before	77	22	322	213	411	262
	After	61	25	309	182	496	259
		NS[f]	NS[f]	NS[f]	NS[f]	S[g]	NS[f]

[a] Serious visible injury
[b] Minor visible injury
[c] No visible injury
[d] Normal weather
[e] Adverse weather
[f] Not significant at 0.05 level of significance
[g] Significant at 0.05 level of significance

TABLE 7 Accident Frequency and Results of Significance Test—Non-Interstate Highways Posted at 55 mph

		Fatal[a]	Injury[b]	PDO[c]	Type2[d]	Type3[e]	Type4[f]
3 Years	Before	1258	37440	71025	5436	22292	17281
	After	1181	34444	68763	4679	19921	16887
		NS[g]	S[h]	S[h]	S[h]	S[h]	S[h]
Quarter 1	Before	233	8323	19048	1049	4639	4224
	After	229	7951	17601	931	4301	4171
		NS[g]	S[h]	S[h]	S[h]	S[h]	NS[g]
Quarter 2	Before	315	9145	14866	1427	5642	3989
	After	209	8055	13850	1190	4840	3762
		S[h]	S[h]	S[h]	S[h]	S[h]	S[h]
Quarter 3	Before	373	9997	25991	1348	5699	4890
	After	295	9532	24655	1211	5253	4981
		NS[g]	S[h]	S[h]	S[h]	S[h]	NS[g]
Quarter 4	Before	337	9976	25991	1348	5699	4890
	After	295	9532	24655	1211	5253	4981
		NS[g]	S[h]	S[h]	S[h]	S[h]	NS[g]

[a] Fatal accidents
[b] Injury accidents
[c] Property damage only accidents
[d] Serious visible injury
[e] Minor visible injury
[f] No visible injury
[g] Not significant at 0.05 level of significance
[h] Significant at 0.05 level of significance

TABLE 8 Accident Frequency by Weather Conditions and Results of Significance Test—Non-Interstate Highways Posted at 55 mph

		Fatal[a]		Injury[b]		PDO[c]	
		Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]
3 Years	Before	1020	246	28115	9325	52193	18832
	After	976	205	25665	8779	51350	17413
		NS[f]	S[g]	S[g]	S[g]	S[g]	S[g]
Quarter 1	Before	152	81	5088	3235	11425	7623
	After	173	56	4962	2989	10976	6625
		NS[f]	NS[f]	S[g]	S[g]	S[g]	S[g]
Quarter 2	Before	270	45	7806	1339	12574	2292
	After	169	40	6549	1506	11475	2375
		NS[f]	S[g]	S[g]	NS[f]	S[g]	NS[f]
Quarter 3	Before	343	30	8617	1380	11298	1822
	After	312	36	7457	1450	10567	2090
		NS[f]	NS[f]	S[g]	S[g]	S[g]	S[g]
Quarter 4	Before	247	90	6605	3371	16896	9095
	After	222	73	6698	2834	18332	6323
		NS[f]	NS[f]	S[g]	NS[f]	S[g]	S[g]

[a] Fatal accidents
[b] Injury accidents
[c] Property damage only accidents
[d] Normal weather
[e] Adverse weather
[f] Not significant at 0.05 level of significance
[g] Significant at 0.05 level of significance

involving only light vehicles increased by 9 percent under normal weather conditions. There were no differences in mean accident rates involving light and heavy vehicles. The number of accidents involving only heavy vehicles decreased by 48 percent.

RURAL NON-INTERSTATE HIGHWAYS POSTED AT 55 mph

The traffic accidents on rural non-Interstate highways posted at 55 mph during the "before" and "after" periods were analyzed. The results are described below (see Tables 7 to 9).

No significant difference in mean fatal accident rates was found on rural non-Interstate highways posted at 55 mph. When the accident data were categorized by weather conditions, fatal accidents under adverse weather conditions decreased by 17 percent in the "after" period. The injury and PDO accidents decreased by 8 and 3 percent, respectively, in the "after" period. When injury accidents were classified by severity, the frequency of serious visible, minor visible, and no visible accidents in the "after" period were found to decrease by various amounts ranging from 2 to 14 percent. When quarterly data were analyzed, it was found that most of the quarters experienced a decrease in injury and PDO accidents, indicating a change in the pattern of accidents in the "after" period.

When the data were categorized by weather conditions and tested for the effects of day of week, time of day, light condition, and vehicle mix, a similar pattern of decrease in accidents was found in the "after" period. Obviously, the reductions in accident rates cannot be attributed to the change in the speed limit. However, the changes can perhaps be attributed to several countermeasures including the seat belt law, speed enforcement, geometric and operational improvements, and so forth that have been implemented on the non-Interstate highways during recent years. An examination of these factors was outside the scope of the study.

CONCLUSIONS

The interaction of speed and accident is a complex phenomenon, which becomes more complicated because of the effects of weather, season, day of week, time of day, light conditions, and vehicle mix. The statistical analysis calculated the mean rates of accidents (that is, the number of accidents per month) and tested the hypothesis that the rates during the "before" and "after" periods are the same.

On the basis of the statistical analysis, it is concluded that the mean fatal accident rate on rural Interstate highways posted at 65 mph in Ohio has not adversely changed after the implementation of the 65-mph speed limit. There were some increases in mean injury and PDO accident rates on these highways during the 36 months after the increase in the speed limit.

Mean fatal accident rates on rural Interstate highways posted at 55 mph increased in the "after" period. However, when the data were categorized according to weather conditions, no adverse change in mean fatal accident rates was found.

TABLE 9 Injury Accident Frequency by Weather Conditions and Results of Significance Test—Non-Interstate Highways Posted at 55 mph

		Type2 Injury[a]		Type3 Injury[b]		Type4 Injury[c]	
		Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]	Norm.[d]	Adv.[e]
3 Years	Before	4335	1101	17037	5255	12505	4766
	After	3765	914	15280	4641	12059	4828
		S[g]	S[g]	S[g]	S[g]	S[g]	NS[f]
Quarter 1	Before	709	340	2908	1731	2459	1765
	After	659	272	2802	1499	2457	1714
		NS[f]	S[g]	NS[f]	S[g]	NS[f]	NS[f]
Quarter 2	Before	1243	184	4855	787	3334	655
	After	1025	165	4035	805	2924	838
		S[g]	NS[f]	S[g]	NS[f]	S[g]	S[g]
Quarter 3	Before	1448	163	5468	844	3550	630
	After	1167	179	4663	864	3292	680
		S[g]	NS[f]	S[g]	NS[f]	S[g]	NS[f]
Quarter 4	Before	934	414	3806	1893	3164	1726
	After	913	298	3780	1473	3386	1595
		NS[f]	S[g]	NS[f]	S[g]	S[g]	S[g]

[a] Serious visible injury
[b] Minor visible injury
[c] No visible injury
[d] Normal weather
[e] Adverse weather
[f] Not significant at 0.05 level of significance
[g] Significant at 0.05 level of significance

Injury and PDO accident rates on rural Interstate highways posted at 55 mph decreased and showed no indication of an adverse spillover effect in the "after" period.

The mean fatal accident rate on non-Interstate highways posted at 55 mph has not adversely changed after the implementation of the 65-mph speed limit and has decreased under adverse weather conditions. Injury and PDO accidents as well as the severity of accidents have decreased, perhaps indicating the positive effects of the seat belt law, speed enforcement, and geometric and operational improvements during recent years. Whether the accidents would have further decreased in the (hypothetical) absence of the 65-mph speed limit can only be speculated on. Some effects of time of day, day of week, and light conditions have been noted in the results; however, further study is needed to isolate the exact relationships among these factors.

ACKNOWLEDGMENTS

This study was funded by the National Highway Traffic Safety Administration. ODHS administered the funds, provided the data that served as a basis for analysis, and supervised the overall work program. The authors express appreciation to Richard D. Paddock of ODHS for his assistance in the conduct of the study.

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Publication of this paper sponsored by Committee on Traffic Law Enforcement.

Statistical Method for Identifying Locations of High Crash Risk to Older Drivers

Gary A. Davis and Konstantinos Koutsoukos

Effective use of finite roadway improvement budgets to accommodate an increasing number of older drivers requires that we be able to identify locations where older drivers appear to have a heightened accident risk. Ideally, the accident records from a location (such as a particular intersection) should provide the information needed to assess the risk experienced there by a given group of drivers, but the lack of location and age-specific measure of exposure coupled with the relatively small accident samples available for particular locations makes the standard methods of high-hazard identification inapplicable. The way in which, by using an induced exposure approach, it is possible to test for the equality of group-specific accident rates at a given site by testing for the equality of two binomial probabilities arising from a particular type of contingency table is described. How an Empirical Bayesian approach to computing point and interval estimates for binomial probabilities, which has appeared in the statistical literature, can be adapted to this problem is described next. The resulting computational procedures are relatively straightforward and can be implemented on a microcomputer. The method is illustrated using accident data for a set of signalized intersections located on a Minnesota highway.

It is a well-established demographic fact that individuals born between 1947 and 1957 constitute a substantial fraction of the current U.S. population, and as these "baby-boomers" age, older drivers will make up an increasingly significant proportion of roadway users. Current road design standards and traffic engineering practice, however, developed during times when older drivers constituted a small minority of the driving population, so that roadway managers have begun to consider whether anticipatory roadway improvements might be needed to block a future increase in traffic accidents (*1*). The value of such improvements depends first on whether older drivers actually have more difficulty with the existing roadway than do younger drivers and, second, on being able to reliably identify locations that actually cause the difficulty. There is mounting evidence that after about the age of 55 or 60, the accident rate for drivers tends to increase (*1,2*). The problem of identifying locations showing increased accident rates for older drivers is the subject of this paper.

The Minnesota Department of Transportation (MNDOT) has projected that the proportion of older drivers in the state's driving population will increase during the next 20 years and that older drivers appear to be overrepresented in traffic crashes (*3*). This has led to a proposed program of roadway improvements intended to enhance older driver safety, including increased use of channelization and control at intersections, improved visibility of roadway markings and signing, and improved positive guidance. Efficient use of limited resources, however, requires identifying those areas where older drivers are at greatest risk and improving these locations first. During the spring of 1990, the authors of this paper began a research project aimed at identifying locations where older drivers were overrepresented in the accident records, but it soon became apparent that statistical identification of such high-risk areas from accident records was a nontrivial task, for which appropriate statistical tools were not available. In response to this problem, we have been able to combine the induced exposure model for estimating group-specific accident risk with an Empirical Bayesian (EB) estimation procedure, producing a flexible and computationally tractable statistical tool.

CLASSICAL AND EMPIRICAL BAYESIAN HAZARD IDENTIFICATION

Traffic accidents are fortunately "rare events" compared with the amount of travel done by the population generating them, so the Poisson distribution provides the statistical model for much accident analysis. More formally, if n_k denotes the actual number of accidents counted over some time period (typically 1 or more years) at a location k, n_k is assumed to be a Poisson random variable with mean value $m_k = \lambda_k E_k$, where λ_k is the accident rate at location k and E_k is the exposure of the traveling population at k.

The accident rate λ_k is thus a measure of the proclivity of location k to produce accidents, with locations having higher values of λ_k being more dangerous. The exposure E_k is a measure of the size of the population at risk, with standard measures of exposure used in traffic accident analysis being the total traffic count at a location, used primarily for analysis of intersections, and vehicle miles of travel, used for roadway

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sections. Given a count of the number of accidents over a period of time at some location and exact knowledge of the exposure during the same time period, the maximum likelihood (ML) estimator of the accident rate is

$$\hat{\lambda}_k = \frac{n_k}{E_k} \qquad (1)$$

"High-hazard" locations can be identified by computing the estimated rate for each location of interest and then selecting those locations where the estimated accident rates are large compared with some regionwide average. Two common methods for high-hazard identification, the accident rate method and the rate quality control method (*4*), are based on the estimator of Equation 1.

It turns out, however, that $\hat{\lambda}_k$ is often a poor predictor of future accident rates due to its failure to correct for a statistical phenomenon called regression-to-the-mean (RTM) (*5*). In plain terms, RTM refers to the tendency of extreme random values to be followed by less extreme values, even when no change has occurred in the underlying mechanism generating these values. Since the variance of the estimator $\hat{\lambda}_k$ is inversely proportional to the exposure E_k, the RTM effect will be more pronounced for those locations with low exposures, and a hazard identification method based on a ranking of the estimates $\hat{\lambda}_k$ will tend to confound genuinely hazardous sites with locations whose extreme values are due to chance alone, leading to an overemphasis of the hazard at sites with lower exposures.

Beginning with Hauer (*5*), a number of accident researchers have worked at improving the ability to identify high-hazard locations through the application of "shrinkage" or EB statistical techniques, and this work has reached a useful degree of maturity in the EBEST methodology developed at the Texas Transportation Institute (*6*). This methodology begins with a Bayesian model in which accidents are assumed to be generated by a two-step probabilistic process. First, a common underlying gamma random variable with mean λ and variance λ/ε generates the accident rates λ_k for each site, and then the actual accident counts are generated as Poisson outcomes as described above. If, in addition to knowing the exposures E_k and the accident counts n_k, one also knows the values of the gamma parameters λ and ε, it can be shown that the Bayes estimator of the accident rates is given by

$$\lambda_k^* = \left(\frac{E_k}{E_k + \varepsilon}\right)\hat{\lambda}_k + \left(\frac{\varepsilon}{E_k + \varepsilon}\right)\lambda \qquad (2)$$

The Bayes estimator is a convex combination of the ML estimator given in Equation 1 and the underlying gamma mean. For those sites with high exposures (and hence lower variances for λ_k) the Bayes estimator tends to weight the ML estimator more heavily, whereas sites with low exposures are "shrunk" more toward the gamma mean. The parameter ε measures the degree of relatedness among the site-specific accident rates, with $\varepsilon = 0$ being the case where the individual λ_k have no relation (so that $\lambda_k^* = \hat{\lambda}_k$), whereas $\varepsilon = \infty$ corresponds to the case $\lambda_k = \lambda$ (i.e., all the individual accident rates are equal to the gamma mean). For intermediate values of ε, the Bayes estimators will tend to be closer (in the mean-square sense) to the true accident rates than will the ML estimator. In most practical situations however, the values of λ and ε will be unknown and also require estimation. EB methods attempt to capitalize on the desirable properties of the Bayes estimator by first replacing ε and λ in Equation 2 with efficient estimates, such as ML estimates, and second, by accounting for the increased uncertainty that results from having less than perfect knowledge of these parameters (*7,8*).

INDUCED EXPOSURE MODEL

In principle, the preceding method of analysis could be extended to the identification of locations where older drivers are overrepresented by simply allowing each age group of drivers to have differing accident rates and exposures at each location of interest. Thus we can define

λ_{ik} = accident rate or risk for age group i at location k,
E_{ik} = exposure of age group i at location k, and
n_{ik} = observed number of accidents for age group i at location k (n_{ik} is assumed to be a Poisson random variable with mean $m_{ik} = \lambda_{ik}E_{ik}$).

Given observations of n_{ik} and E_{ik} for all groups and locations, one could not only identify those locations where older drivers are overrepresented (indicated by high values of m_{ik}) but also attribute the overrepresentation to overexposure (indicated by high values of E_{ik}), greater risk (indicated by high values of λ_{ik}), or a combination of these effects. This methodology is strictly appropriate, however, only when the exposures E_{ik} can be treated as known constants in the analysis. In practice such measures of exposure are derived from a location's average daily traffic (ADT), which in turn is usually estimated from randomly varying traffic count data, so that ADT (and hence exposure) is more properly treated as an additional parameter to be estimated, rather than as a known constant. The current state of the art is such that the statistical properties of various methods for estimating ADT are not well understood, whereas the relationship between ADT estimates and the resulting estimates of accident risk such as Equation 1 are even less clear. These statistical questions are academic, however, since disaggregated measures of exposure for single locations are not generally available and can only be obtained by the expensive and time-consuming expedient of stopping and sampling vehicles at the location.

The difficulties inherent in obtaining good estimates of exposure have been known for some time and have motivated a number of researchers to develop measures of exposure that rely only on data contained in the accident records themselves (*9*). The basic idea of this "induced exposure" method is that for a majority of two-vehicle accidents, one driver can be identified as at fault, whereas the other is an innocent victim. At-fault drivers are assumed to be subject to accidents according to the above Poisson model, whereas victims are assumed to be randomly selected in proportion to their exposures at a location. Thus the proportion of an age group in the victim total gives a measure of the relative exposure of that age group at a location and offers a method for untangling the contributions of risk and exposure for particular age groups. This idea appears to have originated with Thorpe (*10*), enjoyed intense but brief research interest in the early 1970's

(*11–13*), and more recently has been resurrected by researchers at the University of Michigan to investigate the relative hazard for older drivers at different types of intersection (*2*). The Michigan methods are essentially deterministic procedures, however, and though they are useful when dealing with large aggregations of accident records, the lack of a foundation in statistical theory makes them inappropriate in small sample situations. Fortunately, there does exist a natural connection between the induced exposure model and statistical theory, which will now be made explicit.

To simplify the resulting notation, we will treat the case where the population of interest has been divided into only two age groups, "younger" and "older," with λ_{yk} and E_{yk} denoting the risk and exposure for the younger group at location k and λ_{ok} and E_{ok} denoting the corresponding quantities for the older group. This covers most cases of interest, but extension to more complicated classifications appears possible through the use of multinomial and Dirichlet random variables in place of the binomial and beta random variables used here. We then define the following quantities:

r_k = $E_{ok}/(E_{yk} + E_{ok})$, the relative exposure of the older group at location k;
p_k = $\lambda_{ok}E_{ok}/(\lambda_{ok}E_{ok} + \lambda_{yk}E_{yk})$, the relative involvement of the older group at location k;
x_k = the total number of two-vehicle accidents at location k for which an older driver was the at-fault driver;
y_k = the total number of two-vehicle accidents at location k for which an older driver was the innocent victim; and
n_k = the total number of two-vehicle accidents at location k.

Under the induced exposure hypothesis, r_k gives the probability that a driver who has an accident "selects" an older driver as the victim, and p_k gives the probability that a given two-vehicle accident has an older driver as the at-fault party. When the two-vehicle accidents at a location are cross-classified by the ages of the drivers involved, the resulting cell counts will also have Poisson distributions, and by exploiting well-known properties of Poisson and multinomial random variables it can be shown that when the accident total n_k is given, the cross-classification counts form a multinomial random vector. The marginal total x_k is now a binomial random variable with parameters n_k and p_k, and the marginal total y_k is binomial with parameters n_k and r_k. Next, from the definitions of p_k and r_k it is straightforward to verify that the condition $\lambda_{ok} = \lambda_{yk}$ is true if and only if the condition $p_k = r_k$ is also true, so that under the induced exposure model, the problem of testing whether two age groups have the same accident rate at a given location reduces to the problem of testing whether two binomial probabilities arising from a cross-classification table are equal. The ML estimators of p_k and r_k are given by

$$\left.\begin{aligned}\hat{p}_k &= \frac{x_k}{n_k}\\ \hat{r}_k &= \frac{y_k}{n_k}\end{aligned}\right\} \qquad (3)$$

and if the number of accidents at a site is large (i.e., 50 or more) the hypothesis $p_k = r_k$ can be tested using asymptotic likelihood ratio methods (or equivalently, asymptotic methods for contingency table analysis) (*14*). In practice, however, $n_k \geq 50$ is likely to be the rare exception rather than the rule, so that asymptotic methods of hypothesis testing become suspect, and the ML estimators $\hat{p}_k$ and $\hat{r}_k$ become subject to more pronounced RTM effects. Since our problem is essentially one of hypothesis testing rather than point estimation, EB procedures such as those described above are not directly applicable. In the statistical literature, though, Albert (*15*) has presented methods for computing both point and interval EB estimates of binomial probabilities. This methodology can be adapted to produce not only EB point estimates of the quantity $(p_k - r_k)$ for each location but also approximate EB confidence intervals for these differences. A decision rule for identifying which sites satisfy $p_k = r_k$ (and hence $\lambda_{ok} = \lambda_{yk}$) can then be based on whether a confidence interval for the difference $(p_k - r_k)$ contains the value zero. Before proceeding to methods for computing these confidence intervals, we note that the ratio p_k/r_k can be interpreted as the "involvement ratio" used in other studies using induced exposure methods (*2*). Our preference for the difference $(p_k - r_k)$ stems from the fact that, as will be shown later, the probability distribution of this difference can be readily approximated by a normally distributed random variable, allowing the use of z tables in determining probability values. The distribution of the ratio p_k/r_k, on the other hand, is less tractable.

EB ESTIMATION FOR THE INDUCED EXPOSURE MODEL

To illustrate how Albert's formulas can be applied to the problem at hand, we will discuss, in some detail, the problem of estimating the probabilities p_k for a set of locations, and then simply note that estimation of the r_k is exactly parallel. As with the preceding model for accident rates, the EB procedure assumes that the values x_k are generated by a two-step random mechanism, only this time the parameters p_k are assumed to be assigned to locations as the outcomes of a beta random variable with mean value p and variance $p(1 - p)/(m_1 + 1)$. Given p_k and n_k, x_k is then assumed to be a binomial outcome. If the parameters p and m_1 are known, the Bayes estimator of p_k takes the form

$$p_k^* = \left(\frac{n_k}{n_k + m_1}\right)\hat{p}_k + \left(\frac{m_1}{n_k + m_1}\right)p \qquad (4)$$

Albert then places "noninformative" prior distributions on the parameters p and m_1, producing a three-step pure Bayesian procedure. In principle, all quantities of interest, such as point and interval estimates, can be computed through integration of this Bayesian model's full joint probability distribution, but a computationally simpler approach results by using an EB estimator of the form

$$\tilde{p}_k = \left(\frac{n_k}{n_k + \hat{m}_1}\right)\hat{p}_k + \left(\frac{\hat{m}_1}{n_k + \hat{m}_1}\right)\hat{p} \qquad (5)$$

where $\hat{p} = (\Sigma x_k/\Sigma n_k)$ is an unbiased estimator of p, and Albert estimates m_1 using an approximate Bayesian procedure. Rather than use Albert's estimator of m_1, which for our problem would apply the same degree of shrinkage to each location regardless of the individual accident counts, we propose estimating m_1 as the value that maximizes the function

$$f(m) = \frac{\displaystyle\int \prod_{k=1}^{N} \left[\binom{n_k}{x_k} \frac{\beta(mp + x_k, m(1 - p) + n_k - x_k)}{\beta(mp, m(1 - p))} \right] \frac{dp}{p(1 - p)}}{m} \tag{6}$$

Here $\beta(a, b)$ denotes the beta integral evaluated at the values a and b, and since the function $f(m)$ is proportional to the posterior probability density of m_1 based on Albert's noninformative prior distributions for the parameters p and m_1 (*15*, p. 137), $\hat{m}_1$ is, in fact, a maximum a posteriori (MAP) estimator. Albert also provides an approximation to the posterior variance of p_k given the data x_k, which takes the form

$$\nu_{pk} = \left(\frac{n_k}{n_k + \hat{m}_1}\right)\frac{\tilde{p}_k(1 - \tilde{p}_k)}{n_k + 1} + \left(\frac{\hat{m}_1}{n_k + \hat{m}_1}\right)\frac{\hat{p}(1 - \hat{p})}{\sum n_k + 1} \tag{7}$$

Formula 7 is used rather than the estimated posterior beta variance $(\tilde{p}_k(1 - \tilde{p}_k)/(\hat{m}_1 + n_k + 1)$ to partially account for the added uncertainty incurred by using estimates of p and m_1 instead of their true values. Finally, approximate EB confidence intervals for the p_k can be computed by treating the posterior density of p_k given the data $(x_1, \ldots, x_N)$ as a beta density with mean given by Equation 6 and variance given by Equation 7, and then using a routine that computes the inverse of a beta distribution function. Such routines are commonly available in scientific subroutine packages such as IMSL or NAG.

By treating the r_k as outcomes of a beta random variable with parameters r and m_2, EB estimates for the r_k can be computed in a manner analogous to the p_k case. An EB estimate of the difference $d_k = (p_k - r_k)$ is then given by

$$\tilde{d}_k = \tilde{p}_k - \tilde{r}_k \approx E[p_k - r_k | x_1, y_1, \ldots, x_N, y_N] \tag{8}$$

and the variance of this estimator is estimated via

$$\nu_{dk} = \nu_{pk} + \nu_{rk} \tag{9}$$

Confidence intervals for the differences d_k could now be computed using the probability distribution for the difference between two beta random variables, but the resulting need for numerical integration and special software can be avoided by exploiting the fact that the difference between two beta random variables is approximately a normal random variable. That is, conditional upon available data $(x_1, y_1, \ldots, x_N, y_N)$, the random variable $d_k = (p_k - r_k)$ is approximately normally distributed with mean given by Equation 8 and variance given by Equation 9. Approximate EB confidence intervals can then be computed easily using the standard normal distribution.

EXAMPLE APPLICATION

To illustrate these methods, we present the following example. Accident records for the years 1988–1990 were obtained from MNDOT for the 29 signalized intersections on Minnesota Trunk Highway (MNTH) 65 running from the city of Columbia Heights northward into Anoka County. Minnesota's accident reporting form allows the investigating officer to identify, for each driver involved in an accident, one or more actions believed to have contributed to the occurrence of the accident, and so from the data set we selected the records for all two-vehicle accidents for which (*a*) the ages of both drivers were known and (*b*) one driver had one or more contributing factors cited and the other had "no improper driving" cited. The driver with contributing factors cited was then identified as the "at-fault" driver, and the other was identified as the "innocent victim." The ages of both at-fault and innocent drivers were divided into three groups: "younger" corresponding to ages 15–24, "middle" corresponding to ages 25–54, and "older" corresponding to ages 55 or more, and EB estimation methods were used to identify locations of increased risk both for older versus middle drivers and for younger versus middle drivers. All computations were performed using MATHCAD, an interactive formula processing program, on an IBM PS/2 55SX microcomputer. The most computationally demanding task was maximization of the function $f(m)$ to produce MAP estimates of the parameters m_1 and m_2. This was done by using a closed form expression for the ratio of beta integrals appearing in Equation 6:

$$\frac{\beta(mp + x_k, m(1 - p) + n_k - x_k)}{\beta(mp, m(1 - p))} = \frac{\displaystyle\prod_{i=0}^{x_k - 1} (mp + i) \prod_{i=0}^{n_k - x_k - 1} (m(1 - p) + i)}{\displaystyle\prod_{i=0}^{n_k - 1} (m + i)} \tag{10}$$

This permitted use of a univariate numerical integration routine to compute the right-hand side of Equation 6 for any given value of m. Maximization of this expression with respect to m was then accomplished using a dichotomous line-search method.

Before proceeding to the identification of the high-risk locations, we believed it desirable to test whether the assumption that p_k and r_k are generated by beta random variables was in fact plausible for this data set. Following Box (*16*) these tests were based on the marginal distributions for the data x_k and y_k obtained by integrating out the p_k and r_k from their respective joint distributions. For instance, the marginal distributions of the random variables x_k are given by

$$P_k(j) = \text{Prob}[x_k = j | m_1, p] = \binom{n_k}{j} \frac{\beta(m_1 + j, m_1(1 - p) + n_k - j)}{\beta(m_1 p, m_1(1 - p))} \tag{11}$$

whereas the means and variances of the ML estimates $\hat{p}_k = (x_k/n_k)$ are given by

$$\left.\begin{aligned} E[\hat{p}_k | m_1, p] &= p \\ \text{var}[\hat{p}_k | m_1, p] &= \frac{p(1 - p)}{(m_1 + 1)}\left(1 + \frac{m_1}{n_k}\right) \end{aligned}\right\} \tag{12}$$

TABLE 1 Parameter Estimates and Goodness-of-Fit for Younger Driver Data

Involvement Parameters (p_k)		Exposure Parameters (r_k)	
p=.408	m_1=36.9	r=.274	m_2=39.4
t=-0.38	p>.10	t=-0.27	p>.10
X^2=23.0	p>.10	X^2=21.4	p>.10

Now in principle, the predictive distribution, Equation 11, and its consequences provide a means for checking the adequacy of an underlying statistical model, but, in practice, the theory for model checking is less well understood than that for parameter estimation and hypothesis testing (*17*). Fortunately, it is still possible to provide some rough tests of model adequacy. First, if the underlying beta model is valid, then by replacing the p and m_1 in Equation 12 with estimates, it should be possible to transform the sequence of $\hat{p}_k$ (and similarly the sequence of $\hat{r}_k$) into a sequence of random variables with means equal to 0 and variances equal to 1, and tests for these properties can be performed using standard t and chi-squared statistics (*18*). Second, Box (*16*) has suggested that the adequacy of a beta-binomial model, such as that used here, could be checked using the statistic

$$S_{pk} = \text{Prob}\,\{j{:}P_k(j) \leq P_k(x_k)\} \qquad (13)$$

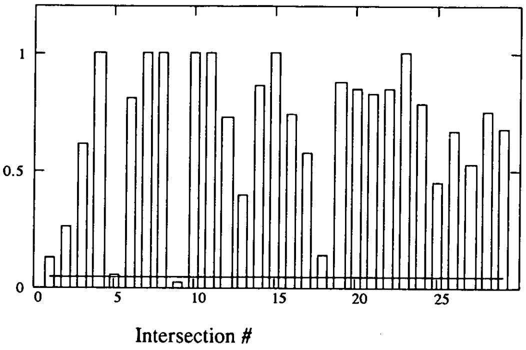
where $P_k(j)$ is the predictive distribution given in Equation 11. From the definition given in Equation 13, it follows that S_{pk} attains its maximum value of 1.0 when x_k equals the mode of the predictive distribution, and that, under the null hypothesis that x_k is an outcome of the predictive distribution, S_{pk} is its own significance level. For example, S_{pk} = .05 can be interpreted as meaning that if x_k actually follows the predictive distribution, the probability of obtaining a value of S_{pk} less than or equal to .05 by chance is equal to .05. Computing the statistic S_{pk} for each location k then allows us to not only assess the general compatibility of the prior distribution with the data but also to identify locations that may be "outliers" with respect to the prior.

Table 1 presents the estimates of p, r, m_1, and m_2 obtained for the younger versus middle data, along with the above described goodness-of-fit tests computed for both the $\hat{p}_k$ and the $\hat{r}_k$. Table 2 gives similar information for older versus middle data. Figures 1 and 2 show the statistics S_{pk} and S_{rk} for the two data sets. The horizontal lines in Figures 1 and 2 correspond to significance levels of α = .05. For the most part, it appears that the beta priors placed on the p_k and r_k are tenable, although Intersections 3 and 5 for the older driver data and Intersections 5 and 8 for the younger driver data might be considered atypical compared with the other locations, and thus candidates for a more detailed investigation.

TABLE 2 Parameter Estimates and Goodness-of-Fit for Older Driver Data

Involvement Parameters (p_k)		Exposure Parameters (r_k)	
p=.240	m_1=46.5	r=.192	m_2=16.9
t=0.39	p>.10	t=-0.07	p>.10
X^2=21.4	p>.10	X^2=24.2	p>.10

Predictive and Data Probabilities for xk



Predictive and Data Probabilities for yk

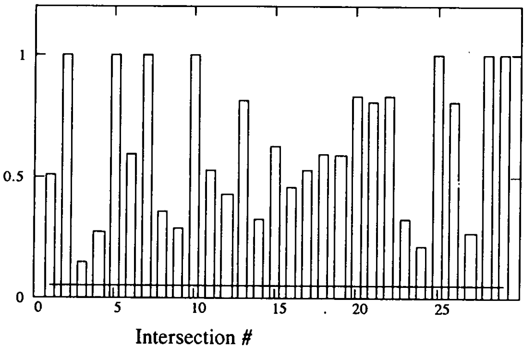
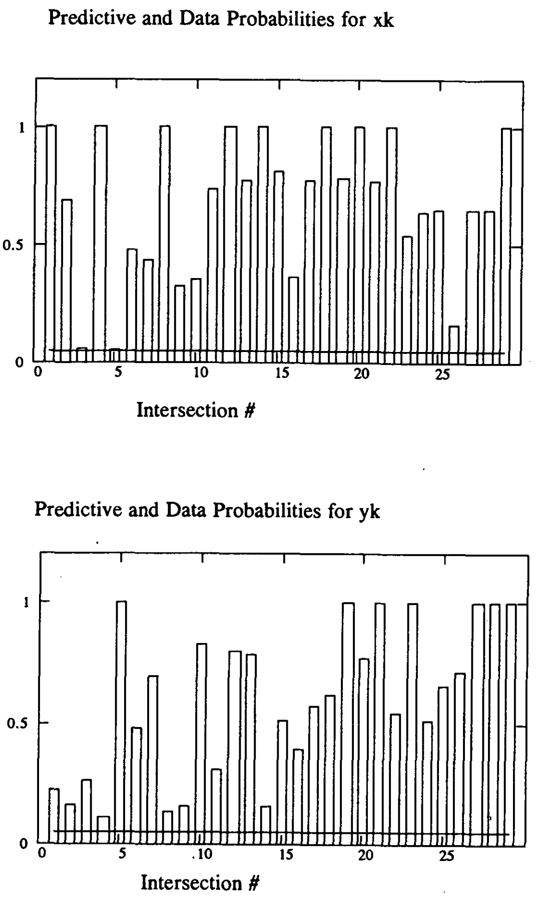


FIGURE 1 Comparison of predictive and data probabilities for younger driver data.

Next, to check the accuracy of the normal approximation used in computing EB confidence intervals, the upper and lower bounds of a nominal 90 percent confidence interval were computed using the normal approximation for each intersection and each data set. Using numerical integration, it was then possible to compute the confidence level that Albert's beta approach would assign to these same intervals. Table 3 gives the computed beta confidence levels for the two data sets. In almost all cases the difference between the nominal and computed confidence levels is less than or equal to 2 percentage points, and we concluded that the normal approximation showed acceptable accuracy.

Finally, Figure 3 shows the EB interval estimates for the difference ($p_k - r_k$) for each intersection along with the ML estimated differences ($\hat{p}_k - \hat{r}_k$). In all cases, the confidence interval is an approximate 90 percent interval computed using the normal approximation. Inspection of Figure 3 shows first that the EB estimates have considerably less scatter than do the ML estimates and that the EB estimates eliminate certain counterintuitive cases from consideration (such as Intersec-


Predictive and Data Probabilities for xk

Predictive and Data Probabilities for yk

FIGURE 2 Comparison of predictive and data probabilities for older driver data.

TABLE 3 Beta-Derived Confidence Levels for Nominal 90 percent Confidence Intervals

Intersection	Younger Driver Data	Older Driver Data
1	.893	.899
2	.901	.897
3	.904	.884
4	.911	.897
5	.901	.908
6	.896	.893
7	.905	.886
8	.911	.907
9	.904	.887
10	.910	.895
11	.913	.915
12	.901	.889
13	.885	.903
14	.906	.912
15	.902	.907
16	.889	.888
17	.914	.894
18	.905	.905
19	.915	.895
20	.902	.903
21	.901	.894
22	.902	.910
23	.883	.891
24	.879	.899
25	.905	.898
26	.898	.888
27	.899	.900
28	.902	.900
29	.882	.892

tion 4, where the ML estimate indicates that middle drivers have higher accident rates than do older drivers). Second, the tendency for younger drivers to have higher accident rates seems to be a somewhat pervasive feature of the entire roadway segment, whereas the increased accident rates for older drivers, if present at all, appear to be localized around Intersections 5 through 7 and Intersections 23 through 25. Assuming that some older driver–oriented improvement of this roadway was desirable, these two sections would be candidates for first consideration.

CONCLUSION

We have presented a statistical method for location-specific testing of the equality of accident rates experienced by two different groups of drivers. To sidestep the need for location- and group-specific measures of exposure, we have based the method on the induced exposure model, and to improve the estimation in the face of the RTM effects inherent in the small samples generally available, we have used an EB estimation procedure. The most computationally demanding feature of our method is the combined numerical integration and univariate line-search needed to compute MAP estimates of the parameters m_1 and m_2. Since a closed form expression can be given for the ratio of the beta integrals appearing in Equation 6, this optimization problem can be solved on a microcomputer using either commonly available computer languages or commercially available mathematical spreadsheet software such as MATHCAD. All other computations require no more than a hand calculator. Thus the method should be easy to incorporate in any accident analysis system capable of matching accident records to specific locations and potentially could be used for cost-effective screening of a large number of locations as to their hazard for particular driver groups, such as older drivers.

Before recommending widespread implementation of the method, however, we believe that three issues require further study. First and foremost, the question as to whether the method is robust with respect to different choices for the noninformative prior distributions placed on the hyperparameters p, r, m_1, and m_2 needs investigation. Second, the robustness of the method with respect to different procedures for estimating the hyperparameters should also be investigated. Third, it may be possible to reduce the computational effort required by the current implementation of this method through the use of more efficient search routines such as Golden Section search or less demanding approximations to the numerical integrals used here. Given suitable answers to these questions, the combination of EB statistical methodology with the induced exposure model should provide a useful addition to the safety engineer's analytic toolbox.

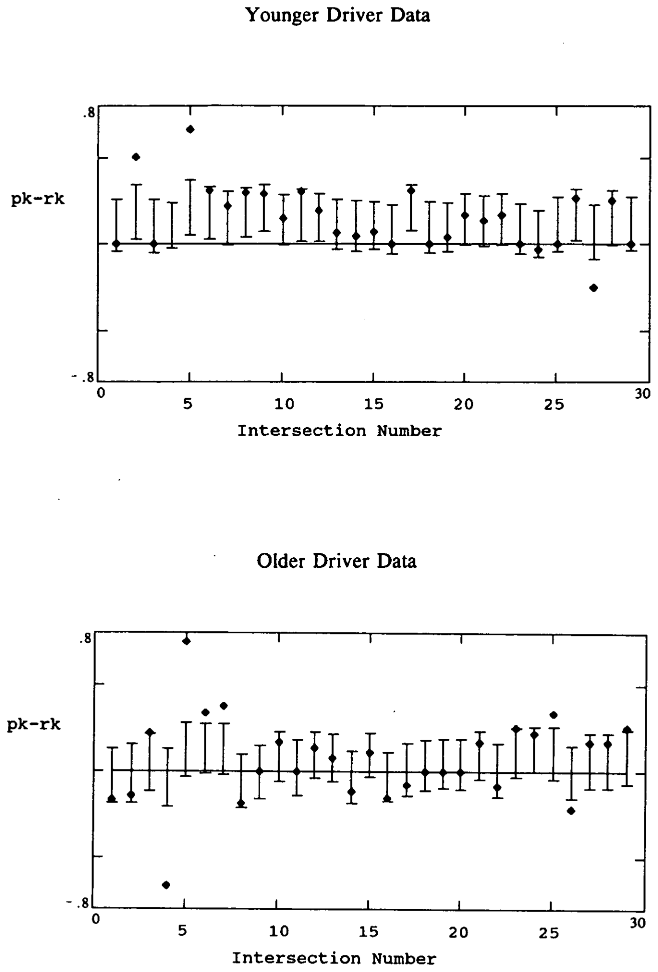


FIGURE 3 Comparison of 90 percent EB confidence intervals (I) and ML point estimates (◆) of the differences $p_k - r_k$.

ACKNOWLEDGMENTS

The authors thank Dave Miller of MNDOT for developing the accident data files used in this research. They also thank Robert Johns of the Center for Transportation Studies at the University of Minnesota for the initial contact work that resulted in this research project.

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This research was sponsored by the Minnesota Department of Transportation, but all opinions and conclusions expressed here are solely the responsibility of the authors.

Publication of this paper sponsored by Task Force on Statistical Methods in Transportation.

Issues of Elderly Pedestrians

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As people age, walking becomes critically important in maintaining mobility. A standardized questionnaire was used to assess the perceptions of 76 elderly citizens ages 56 and over in Orlando, Florida, regarding adequacy of pedestrian crosswalk displays in terms of time and display visibility, the walking routine of the sample members, and their understanding of the cues provided by the display. The majority of those surveyed indicated that the current configuration of the pedestrian crossing signal provides sufficient time to cross the street. However, many expressed concerns for safety and feelings of anxiety and reported an increase in walking pace when crossing the street. Those surveyed lacked information concerning the significance of the signal phases, the meanings of the cue indicators, and knowledge of proper crossing behavior. A quarter of those surveyed did not understand the meanings of the international icons. More than half avoid crossing the street during peak traffic hours and during low visibility, such as at dusk and at night. About a fourth of those sampled had difficulty seeing the crosswalk display. It is recommended that to improve the safety of the walking pedestrian, information concerning the meanings of display cues be provided.

The U.S. Senate Committee on the Aging projects that 15 percent of the United States population will be 65 or older by 2020 (*1*). In Florida, the elderly make up 21 percent of the population. It is projected that this percentage will increase to 25 percent by 2015. Living and working environments must be designed to meet the needs of the aging population. As people age, walking becomes critically important in maintaining their mobility. Walking is the second most relied upon mode of transportation for the elderly (vehicles being the primary mode). Furthermore, the elderly depend more heavily on walking as a means of mobility as their age increases. Thus, to enhance mobility, it is necessary to consider the physical and sensory limitations of the elderly when designing pedestrian crossings.

Densely populated metropolitan areas with high volumes of pedestrian and automobile traffic present a challenging problem for traffic engineers. Pedestrian crosswalks must be designed to allow pedestrians safe passage at regular intervals while maintaining traffic flow. Current standards in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*2*) recommend that crossing signals be installed at intersections with large volumes of pedestrians, school crossing intersections, intersections where pedestrians cross more than one street such as a wide median divided road, and where vehicular indications are not visible to pedestrians.

Currently, several forms of pedestrian displays are in use. The display format is either text or iconic representation. Text has an advantage in that it can convey precisely the message that is intended. However, text can be problematic when individuals' reading skills, language barriers, or visual decrements are involved. Kline et al. (*3*) found that the visibility distance for viewing traffic signs using icons was nearly twice that of signs using text. The icons were particularly beneficial for viewing signs under reduced visibility conditions (e.g., dusk) and for elderly subjects. However, icons require an additional cognitive process and processing time to interpret the meaning of the symbols. These findings are particularly interesting because the MUTCD (*2*) specifies that either icon or text is acceptable to convey the Walk/Don't Walk message, but contrary to the Kline et al. results, the MUTCD (*2*) requires the icon form of the message to be twice as large as the text form.

Universal icons have been adopted to provide cues to the pedestrian (*2*). To designate Walk, the iconic representation is a "walking man." Three different icons are used to represent Don't Walk: a slash through the figure of a walking person, a raised hand; and an upright man in a standing position. Dewar (*4*) noted that prohibitive signs (a slash through an icon) require longer processing times, possibly because the slash partially obscures legibility of the symbol. Robertson (*5*) investigated which icon was most effective at conveying Don't Walk. The use of a prohibitive slash does not meet effective design principles because it obscures the icon when viewed at a distance. However, the prohibitive form of the icon (i.e., a slash through the figure of a person walking) was chosen over the other two icons by 70 percent of the subjects.

The crosswalk display has three distinct temporal phases. The first phase consists of a period during which the word Walk or the walking man icon is illuminated. The second phase consists of a period during which the words Don't Walk or an upraised hand flashes on and off. The final phase consists of a steady illumination of the Don't Walk or upright hand. The duration of the complete crossing display cycle is dependent on the width of the street and the flow of traffic. The MUTCD standard (*2*) is based on the premise that the flashing Don't Walk phase provides enough time for the average pedestrian to travel from the curb to the center of the farthest lane. The standard for the average walking speed is 4 ft/sec (*2*). Intersections that are frequently used by the handicapped elderly may be set at slower speeds to accommodate their special needs.

Proper street-crossing behavior consists of the following actions: During the onset of a steady Walk signal, the pedestrian is to scan the street for oncoming traffic and proceed to cross the street perpendicular to the face of the Walk signal. It is important to scan for traffic making right turns on red and left turns on green even though the pedestrian has the legal right-of-way. When the flashing Don't Walk signal begins and a pedestrian is in the street, the correct behavior is

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to continue crossing the street. If the pedestrian has not begun to traverse the street, the correct behavior is to push any button to "call" the pedestrian signal and wait until the next Walk cycle. The flashing Don't Walk signal indicates proceed with caution. The steady Don't Walk signal is the equivalent of a red signal indicating danger, and it is not safe to enter the street. If the pedestrian is still in the street, the pedestrian should reach the curb as quickly as possible because approaching motorists will not expect a pedestrian to be in the road.

Color provides a secondary cue to the street-crossing pedestrian. The MUTCD standard (*2*) recommends Portland orange to signify Don't Walk and lunar white to indicate Walk. White may produce the best contrast for viewing but has been shown to be associated with the slowest reaction times (*6*).

FACTORS AFFECTING THE PEDESTRIAN WALKING TASK

Environmental Factors

A variety of environmental factors affect the ability of pedestrians to complete the task of crossing the street safely. Environmental conditions, such as rain, fog, snow, dusk, nighttime, and glare, can limit or restrict the visibility of the crossing display. Similarly, both environmental and man-made sources of illumination may present problems of glare and dark adaptation. Without glare protection devices such as hoods or baffles, it is difficult to distinguish which signal is lit under conditions of direct sunlight. Sources of glare include sunlight, headlights, neon, and street lighting. The elderly may have difficulty seeing unprotected displays because of their decrease in contrast sensitivity and lower tolerance of glare.

Another factor affecting the pedestrian crossing task is the complexity of traffic patterns. Busy intersections, multiple lanes, and vehicles turning right on red or left on green make it difficult for pedestrians and motorists to simultaneously attend to all the possible combinations of traffic patterns. This results in many pedestrians in Florida being struck by vehicles while crossing multilane intersections that allow right turns on red or left turns on green, or both (*7*). Moreover, 70 percent of the elderly pedestrian fatalities occur while crossing with the Walk signal illuminated (*7*).

Street conditions such as curb design and pavement maintenance may also affect the safety of pedestrian crossings. Extremely high curbs and curbs without handicap ramps pose a serious problem for the elderly. Cracks and potholes in the crosswalk pavement can also be dangerous for elderly pedestrians, particularly for those using walking aids.

Physiological Factors of Age

Elderly pedestrians are confronted with progressive sensory and physical debilities that may impede their ability to manage the potential hazards at pedestrian crosswalks. Consider, for example, the sensorimotor requirements needed to skillfully traverse the street on which there is a signalized crosswalk. The components of the pedestrian task are to see and press the button on the pole (if any); read and understand the crosswalk instructions (if any exist); see and comprehend the walk display on the other side of the street when it is displayed; listen to scan for traffic; search for and negotiate potholes, curb erosion, gratings, gutters, and other obstructions in the path; and attend to a myriad of other impinging stimuli. Besides the standard "look left, look right, look left" scan pattern, the pedestrian must look over the shoulder to scan for vehicles turning right on red.

Physiological changes that occur with age include impaired vision and audition as well as postural instability and gait disturbances. The following sections provide a brief review of pertinent literature concerning the deterioration of sensory and physical capabilities that affect elderly pedestrians' ability to safely traverse pedestrian crosswalks.

Vision

There is an accelerated decrement in peripheral vision after the age of 50 (*8*). The loss of peripheral vision increases the elderly pedestrian's chances of not seeing approaching and turning cars from the side. Modern crosswalks typically do not provide a time period in which pedestrians can cross without the threat of simultaneous vehicular turning.

A decline in static acuity, the ability to resolve fine spatial detail in the absence of motion, can affect the elderly pedestrian's ability to read the crossing signal message accurately as well as the crossing instructions on the pole. Decrements in dynamic acuity, the ability to resolve fine spatial detail for objects in motion relative to the observer, can affect the processing of details while the individual is in motion. Sharpe and Sylvester (*9*) demonstrated that older subjects were not able to track accurately objects that moved smoothly across the visual field at a rate of 10 degrees/sec or greater. Rabbit (*10*) found that older subjects were poorer at searching complex patterns. Reduced scanning ability may present problems for elderly pedestrians when scanning the road for traffic and various obstructions while tracking their own movements across the street.

The street-crossing task requires a number of changes in accommodation (e.g., a shift in focus from the curb to the crossing signal). Accommodation is the ability of the eye to focus an image on the retina. The process of accommodation provides depth cues that decline significantly with age (*11*). The decline in depth perception may affect the elderly pedestrian's ability to judge oncoming traffic, the height of curbs, or obstructions in the road. The loss of accommodation can result in blurred vision and disorientation, which may increase the likelihood of falling.

Wolf (*12*) found that the elderly are more sensitive to glare and require higher illumination to identify targets even in the absence of glare. The headlights of oncoming traffic present a major problem because they require more time to recover from the effects of glare (*13,14*). Dark adaptation affects the pedestrian crossing task during dusk and nighttime illumination and presents a potential problem when traversing from a well-lit area to conditions of lower illumination.

Audition

Elderly individuals experience progressive hearing loss with age (*15*), and a decrement in hearing presents obvious problems for the pedestrian. Sounds created by automobiles, trucks, and motorcycles provide aural information regarding oncoming traffic. The elderly pedestrian afflicted with hearing loss may have to rely on visual cues to detect approaching vehicles. Because the noise source is projected from behind the head, pedestrians have greater difficulty perceiving oncoming traffic when their backs are turned away from the traffic.

Cognition

The most prevalent observed change due to age is the slowing of behavior, including simple sensory and motor processes, reaction time, and complex cognitive processes (*16*). The changes in intellectual ability, reasoning, word fluency, verbal comprehension, and educational aptitude are usually minimal up to age 60 (unless there is a specific physiological cause). Slowed cognitive responses, plus not unreasonable increased concern for safety, affect the elderly pedestrian's ability to effectively respond to oncoming cars or unexpected events in the environment. In the absence of walking ramps, the elderly may hesitate to step off the curb. Given circumstances requiring decision making under stress, slowed reaction time and cautiousness may render even a correct action ineffective.

Gait

Drills (*17*) and Molen (*18*) reported a decline in walking velocity, step length, and step rate as age increases. Elderly females were found to walk at a slower pace with a higher cadence and shorter step length than elderly males. It is difficult to determine, however, whether the shortened stride and slower velocity is due to physiological changes alone or to past experiences and fears of falling (*19*). Nonetheless, a shortened stride length may affect their ability to clear street gutters or obstructions. If road surfaces are uneven or their visibility is impaired, the elderly are more cautious in their walking habits (*19*).

The elderly tend to experience a decrease in postural stability because of the systematic degeneration of vestibular, somatosensory, and neural pathways for motor control (*20*). As many as one-half of all persons 65 or older experience a fall each year. Uneven street surfaces may contribute to postural instability, which may increase the probability of falling.

Finally, and perhaps most important, because elderly persons walk more slowly than the general population, they may not have sufficient time to cross the street. A study conducted by Lundgren-Linquist et al. (*21*) compared the walking velocity of 79-year-old pedestrians with the walking standard for crosswalks in Sweden (1.4 m/sec). The subject pool included 112 women and 93 men; walking aids were used by 27 and 25 percent, respectively. The results indicated that none of the subjects could cross the street at the specified rate when using their preferred rate of walking. When instructed to walk at their maximum speed, only 32 percent of the women and 72 percent of males could achieve the 1.4 m/sec standard. The authors concluded that the timing of lights at intersections in Sweden did not meet the functional capacity of older citizens, and therefore the Swedish standard for crosswalk design may be less than optimal.

Crosswalk design parameters that accommodate the sensory and mobility capabilities of the elderly will result in increased performance, reliability, and safety for all. Reduced mobility and the use of walking aids such as a cane or walker may further slow the rate of movement in elderly persons. Impaired balance might also reduce their ability to maneuver over curbs, which might also then increase the time needed to cross the street.

The current study was designed to assess elderly pedestrians' perceptions regarding the following issues: the adequacy of pedestrian crosswalks, knowledge of the display cues, and correct pedestrian crosswalk behavior.

METHOD

A standardized questionnaire was developed to assess the crossing behavior of the elderly and affective components related to the adequacy of pedestrian crosswalk displays. The questionnaire consisted of 25 questions that addressed walking routine; compliance and avoidance behaviors; and perceptions concerning the adequacy of automated street crossings in terms of time, display visibility, and knowledge of display cues. The following demographic data were collected: gender, age, the use of walking aids and corrective lenses, and physical and visual impairments.

Seventy-six senior citizens from various churches and retirement homes in the downtown area of Orlando, Florida, volunteered to participate in the survey. The sample consisted of 19 males and 57 females aged 56 years or older (total n = 76). Sixty-eight percent of those surveyed were older than 75, 9 percent were between 56 and 65, and 20 percent were between 66 and 75. Two of the subjects did not provide their age. Corrective lenses were worn by 86 percent of the sample, and 28 percent reported having cataracts. One-third of those surveyed reported physical impairments that affect their walking ability, and a similar one-third reported using a walking aid, the most common being a cane. However, most indicated that they were physically capable of crossing the street, with only 19 percent indicating that they required assistance when crossing the street. Four respondents (5 percent) reported that they had been hit by a vehicle, and 14 (18 percent) had seen someone hit by a car.

RESULTS

The results were divided into seven categories: intersection behavior, adequacy of the automated street crossing displays, display visibility, affective perception, avoidance behavior, knowledge of display icons, and the comprehensibility of written instructions.

Intersection Behavior

Six questions addressed pedestrian intersection-crossing behavior. These items were basically concerned with which factors elderly pedestrians take into account when crossing the street and whether their crossing behavior conforms to safety regulations and guidelines. Crossing the street at nondesignated areas does not appear to be a problem. A majority (86 percent) indicated that they frequently or always cross only at designated crosswalks; 57 percent indicated that they frequently or always press the button on the crosswalk pole to change the crossing signal.

When asked which cues they use to cross the street, 91 percent responded that they frequently or always use the steady Walk symbol, 72 percent use the red traffic light, and 69 percent use the flow of traffic to indicate that it is safe to cross the street. In addition, 97 percent of the respondents indicated that they frequently or always wait for the traffic light to turn red before crossing the street.

Adequacy of Automated Street Crossing

The survey data indicated that 55 percent of the elderly frequently or always hurry across the street. The majority (87 percent) reported that they increase their pace even more when the flashing Don't Walk signal is displayed.

Affective Behavior

Although they increase their pace when crossing the street, a majority (77 percent) indicated that they have enough time to cross the street and that the time allotted was adequate for safe crossing. However, crossing a busy intersection produces anxiety for 62 percent of those surveyed, and 45 percent reported that they frequently or always worry about getting across the street before the signal changes.

The fear of crossing appears to be widespread among the elderly. Of particular concern is the law that permits vehicles to turn right on a red light after stopping. Nearly three-quarters of respondents reported anxiety about cars turning right on red while they were attempting to cross. This worry is well founded in that accident data show that most pedestrian accidents in Florida occur at an intersection while vehicles are making right turns on red (*7*).

Display Visibility

As discussed earlier, visual performance declines with age. Most design guidelines take this into account by requiring optimal illumination levels, contrast ratios, and oversized lettering. The design specifications used on crosswalk displays appear to be sufficient for most users. However, almost 25 percent of our sample reported difficulty seeing the crosswalk signal from the opposite side of the street.

Avoidance Behavior

The respondents were asked about their walking behavior during peak traffic hours, at night, and at dusk. More than half of the elderly (57 percent) reported that they avoid crossing the street at peak traffic hours. In addition, 51 percent avoid crossing the street at dusk, and 58 percent avoid crossing the street at night.

Knowledge of Display

Only 31 percent of the respondents knew that a flashing Don't Walk signal meant proceed with caution. The majority (64 percent) thought the flashing signal meant danger. There appears to be some confusion concerning proper crossing behavior. About one-third of the respondents indicated that they would return to the sidewalk when the signal begins to flash. Although a flashing Walk is not used in the geographic area in which the data were collected, a majority of the sample (75 percent) thought this display meant caution. A flashing Walk cue used to warn the pedestrian to be aware of turning vehicles but is no longer in the MUTCD (*2*) precisely because so few pedestrians, of all ages, understood the intended meaning.

The respondents were asked to identify the meaning of three icons that represent Don't Walk: the upright hand, walking man with a slash, and upright man. Seventeen percent did not know the meaning of the prohibitive icon (walking man with slash). Although the upright hand is currently used in the Orlando area, 36 percent could not correctly identify its meaning. A majority of the respondents (69 percent) thought the upright man indicated that it was safe to walk, and 15 percent thought it meant caution. The respondents were asked their signal cue preference (text or icon). The majority (65 percent) preferred text.

Comprehensibility of Instructions

The respondents were asked about the comprehensibility of crosswalk instructions. A majority (62) indicated that the instructions were easy to understand. However, 28 percent indicated they have never read the instructions, and 10 percent indicated that the instructions did not make sense.

DISCUSSION OF RESULTS

On the basis of the survey results, pedestrian crossing signals are perceived to provide sufficient time for the elderly to cross. However, the elderly expressed concerns for safety and feelings of anxiety and tend to increase their walking pace while crossing the street. Their concern for safety and the increase in stride and walking pace may result in a higher probability of falling.

The concern for safety may be related to a general lack of understanding concerning the significance of the signal phases, the meanings of the cue indicators, and knowledge of proper crossing behavior. Individuals in the current sample were unfamiliar with the meaning of the various icons used in signal displays and the significance of the flashing cues and operating characteristics of the displays. Many returned to the sidewalk when the signal began to flash instead of continuing across the street. It is important to provide information concerning the operation and function of the crosswalk displays. The misinterpretation of signal cues may be contributing to the occurrence of traffic accidents involving the elderly and fatalities. Although the meanings of traffic icons are taught in public schools, many of the elderly have not received training in this area. The use of universal icons is relatively new in the United States and may account for the preference for textual displays among the elderly. If the meaning of a pictorial representation is not obvious, it may result in confusion, error, and, in this case, possibly death. The lack of understanding makes it dangerous for the elderly to cross the street. It cannot be assumed that the international icons are understood without additional information.

The elderly avoid crossing the street during peak traffic hours and during low visibility, such as at dusk and at night. This avoidance behavior may be related to the concern for safety and the perceived danger in crossing the street in high traffic volume. The visual decrement that many elderly experience contributes to avoidance behavior under low visibility conditions. About one-fourth of those sampled had difficulty seeing the crosswalk display.

A large percentage of the respondents tend to rely on multiple cues when crossing the street: the red traffic light, the steady Walk signal, and the flow of traffic. Although it is important to attend to the various cues provided, there are some risks involved in attending to the red traffic light or the flow of traffic alone. The vehicles may be legally traveling through an intersection during the first few seconds of the red display and may not have time to stop if a pedestrian has begun to cross the street. Since the elderly pedestrian's reaction time is slower than that of the younger pedestrian, the elderly pedestrian is less able to respond to traffic turning right on red or left on green. Whereas using the flow of traffic as a cue is not an unsafe behavior, it can create unnecessary risks if the pedestrian waits at the curb for an oncoming vehicle to come to a stop, wasting valuable Walk time.

CONCLUSIONS

The following are offered as suggestions to improve the pedestrian crosswalks:

- Post pedestrian signal display explanations at crosswalks and push button operating instructions at pedestrian-activated crosswalks.
- Post potential road hazard signs (i.e., cars turning right on red) on pavement to alert pedestrians.
- Provide general information concerning walking safety. Suggested methods include distributing instruction card or pamphlet to describe safe crosswalk behavior to the general population, not just motorists or the elderly, and providing seminars to target population on how to reduce the risks of walking.
- Control traffic patterns involving a left turn on green by using green arrow for permissible turns where there are significant numbers of elderly, children, handicapped, or other target pedestrian groups. The green arrow cannot be displayed during the pedestrian Walk phase.
- Provide warning cues to motorists at intersections where pedestrian crossings are the unexpected.

Further research is needed to assess the impact of different types of cues for pedestrian crossings. For example, auditory cues as secondary warning indicators of traffic flow and countdown cues to indicate the amount of remaining time to safely cross the street might provide valuable aids to the elderly pedestrian and the physically impaired. The visibility of text and icon displays should be reevaluated under conditions of dusk, night, and glare. Because of the number of fatalities involving vehicles turning right on red, additional research is needed to investigate the feasibility of mitigating this option, especially in areas with a high concentration of pedestrians.

Basic issues concerning elderly pedestrian behavior need to be researched. For example, how often do they walk, when, under what conditions, do they walk alone or with others, and what crossing strategies do they use to traverse intersections? By understanding the perceptions and issues of the elderly pedestrian, safety issues for all pedestrians can be addressed.

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Publication of this paper sponsored by Committee on Pedestrians.