dent is not remarkably noticeable in the traffic data. Second, work is needed in studying the effect of the data aggregation interval (20, 30, or 60 s) on the detection performance of the algorithm. It is believed that data aggregation induces a masking effect on the actual 0-1 pulses obtained each 0.01-0.25 s from point detectors. Finally, the computational requirements for implementing the ARIMA algorithm by using microprocessors must be examined. As of this writing, the above remarks are being explored.

REFERENCES

1. S.A. Ahmed and A.R. Cook. Analysis of Freeway Traffic Time-Series Data by Using Box-Jenkins Techniques. TRB, Transportation Research Record 722, 1979, pp. 1-9.
2. G.E.P. Box and G.M. Jenkins. Time-Series Analysis: Forecasting and Control. Holden-Day, Inc., San Francisco, CA, 1976.
3. C.L. Dudek. Human Factors Considerations for In-Vehicle Route Guidance. TRB, Transportation Research Record 737, 1980, pp. 104-107.
4. G.N. Saridis and C.S.G. Lee. On Hierarchically Intelligent Control and Management of Traffic Systems. Proc., Engineering Foundation Conference on Research Directions in Computer Control of Urban Traffic Systems, ASCE, New York, 1979, pp. 209-218.
5. K.R. Courage and M. Levin. A Freeway Corridor Surveillance, Information, and Control System. Texas Transportation Institute, Texas A&M Univ., College Station, Res. Rept. 488-8, 1968.
6. R.S. Foote. Development of an Automatic Traffic Monitor and Control System. HRB, Bull. 291, 1961, pp. 79-103.
7. M. Levin and G.M. Krause. Incident Detection--A Bayesian Approach. TRB, Transportation Research Record 682, 1978, pp. 52-58.
8. H.J. Payne and S.C. Tignor. Freeway Incident-Detection Algorithms Based on Decision Trees with States. TRB, Transportation Research Record 682, 1978, pp. 30-37.
9. J.T. West. California Makes Its Move. Traffic Engineering, Vol. 41, No. 4, 1971, pp. 12-18.
10. A.S. Willsky, E.Y. Chow, S.B. Gershwin, C.S. Greene, P.K. Houpt, and A.L. Kurkjian. Dynamic Model-Based Techniques for the Detection of Incidents on Freeways. IEEE Transactions on Automatic Control, Vol. AC-25, No. 3, 1980, pp. 347-360.
11. A.R. Cook and D.E. Cleveland. Detection of Freeway Capacity-Reducing Incidents by Traffic Stream Measurements. TRB, Transportation Research Record 495, 1974, pp. 1-11.
12. C.L. Dudek, C.J. Messer, and N.B. Nuckles. Incident Detection on Urban Freeways. TRB, Transportation Research Record 495, 1974, pp. 104-107.
13. R.H. Whitson, J.H. Buhr, D.R. Drew, and W.R. McCasland. Real-Time Evaluation of Freeway Quality of Traffic Service. HRB, Highway Research Record 289, 1969, pp. 38-50.

Publication of this paper sponsored by Committee on Freeway Operations.

Effects of Rail-Highway Grade Crossings on Highway Users

JAMES L. POWELL

Basic research into effects of rail-highway grade crossings on highway users was conducted. The overall objective was to investigate improved techniques for estimating nonaccident effects, such as excess delay, user costs, direct energy consumption, and pollutant emissions. Numerical results also were desired. A microsimulation model is developed for analyzing delays due to train blockages at grade crossings not affected by other highway system bottlenecks. An analytic model is then developed to estimate effects of a vehicle slowing at grade crossings with no train present due to rough surface conditions. These models are validated to the extent possible based on field studies. A sensitivity analysis reveals that for most practical applications, train blockages can be analyzed more easily by using simple equations. A sample application of the method is presented in which 385 grade crossings are evaluated from which design options have been selected. The model developed for analyzing effects of a vehicle slowing with no train present is recommended for further applications, although more extensive validation studies are desirable. Numerical results indicate that nonaccident costs of grade crossings dominate accident costs in the ratio of about 3.5:1. The effects of a vehicle slowing with no train present dominate effects of train blockages in the ratio of about 2:1. The methods developed are felt to represent a significant improvement over earlier techniques for estimating highway-user effects. The methods can be applied to evaluation of alternatives such as rail relocations, construction of grade-separation structures, and crossing-surface improvements. Areas of further research are also identified.

The majority of research on rail-highway grade crossings has been devoted to accident aspects. That such research has been justified is seen in a steady decline in crossing fatalities over time (1). Safety investigators have delved into various areas, which include design, driver behavior, conspicuity, and predictive accident equations, among others.

In contrast, nonaccident aspects of grade crossings have been studied in much less detail. Although major nonaccident aspects have been identified (2, Chapter 3), the research is not well developed. These nonaccident aspects fall into the following categories: delay and increased operating costs for highway users, community barriers (physical and psychological), environmental degradation, incompatible or inappropriate land uses, and increasing operating costs to railroads. The categories are not necessarily separate from one another.

The most important nonaccident aspects, or at least the most readily quantified, are those associated with highway users, such as excess delay, cost, energy consumption, and vehicle emissions attributable to grade crossings. Generally, it is required that some or all of these effects be explicitly considered in plans to alter crossing conditions. Such plans might include schemes for rail relocation, grade separation, or crossing-surface improvement. For proper evaluation, it is desirable to have readily applied techniques for quantifying all or some of these highway-user effects.

In addition to identifying important nonaccident aspects of grade crossings, prior research has proposed methods to analyze individual effects. With respect to highway-user effects, the general shortcoming in these methods is that they are at a gross level. For example, in the estimation of delays and highway-user costs associated with train blockage of a crossing, one major study (3, Chapter 11) assumes highway vehicle and train volumes to be uniformly distributed over a 24-h day. In reality, both vehicle and train traffic can follow greatly different time patterns over a day, which affects delay behavior a good deal. Another difficulty is that blockage times are averaged such that each train is treated as though it causes the same fixed blockage time. Actually, all other things being equal, the expected vehicle delay of one 10-min train is on the order of four 5-min trains.

The other significant source of impact on highway users at grade crossings is the slowing that takes place due to rough surface conditions. The same major study (3, Chapter 11) has recommended the use of fixed average approach speeds and fixed average crossing (minimum) speeds. In reality, vehicle speeds are known to vary around the average in some regular pattern. In the case of a grade crossing, the degree of variation around average crossing (minimum) speed is expected to be greater than at free-flow locations. Such variations should probably be considered in the analysis.

In summary, it is desirable to analyze in greater detail the effects of grade crossings on highway users. The purpose of this paper is to investigate methods of accomplishing this task and to provide numerical results. In this research, there are few preconceived notions of grade-crossing behavior so that various interactions can be studied in detail. Nevertheless, a major goal is to develop practical techniques that can be useful in many applications.

DEFINITIONS

Highway-user effects of grade crossings originate from two major sources: occurrence and nonoccurrence behavior. Occurrence behavior is defined to be the slowing, stopping, idling, and sluggish movement of highway vehicles that takes place when a train is present. Nonoccurrence behavior is defined to be the vehicle slowing at a grade crossing when no train is present due to real or perceived crossing roughness.

It has been suggested that nonoccurrence behavior--a vehicle slowing when no train is present--is not necessarily a cost, since it causes drivers to proceed more cautiously across the danger zone of a grade crossing. Several studies (4-6) have implicitly or explicitly taken this view in studying high-speed rural or sight-obstructed crossings.

Counter to the above is the point that if drivers have to worry about crossing conditions, their attention is diverted from the primary safety task--looking for a train. This view is particularly apropos of crossings with active protection and is embraced in federal highway programs that provide funds to smooth crossings (7). In the absence of comprehensive accident data, and in view of the fact that many crossings of concern have active protection, the assumption in this paper is that forced slowing due to roughness is a highway-user cost.

It is useful also to distinguish between two general types of crossings: isolated and nonisolated grade crossings. Isolated grade crossings are considered to be independent of other traffic system bottlenecks, primarily signalized intersections. Nonisolated crossings are those that cannot be considered independent, perhaps lying near a signalized intersection. As an initial research effort, this paper focuses almost entirely on isolated grade crossings.

FIELD STUDIES

As a first step in studying grade-crossing behavior, field studies were conducted at four crossings located in Hammond, Indiana (population 110 000). Hammond is an excellent area in which to study urban grade crossings; it is the gateway from the East Coast of the United States to the busiest rail hub in the United States, the Chicago Terminal District. More than 185 trains operate through or within Hammond daily, traversing about 110 grade crossings.

The four study sites included three isolated grade crossings and one nonisolated grade crossing. The nonisolated crossing lay immediately adjacent to a signalized intersection in downtown Hammond. The four study sites are as follows: Columbia and the Baltimore and Ohio Chicago Terminal Railroad (Columbia/B&OCT), Kennedy Avenue and Consolidated Rail Corporation (Conrail) (Kennedy/CR), Hohman Avenue and the B&OCT (Hohman/B&OCT), and Sohl Avenue and Conrail (Sohl/CR). Table 1 summarizes the characteristics of the four sites.

Occurrence data were collected by detailed traffic counts both when trains were present and when they were not. Arrival counts (in 20-s intervals) were used to analyze delay and to develop time-of-day profiles of volume. Departure counts (in 10-s intervals) were made after train occurrences to complete the delay data. In this manner, vehicles delayed and time-delay data were gathered and compiled for 26 train occurrences at the four crossings over four days (8).

The arrival data were also analyzed in terms of statistical patterns. It was hypothesized that the arrival pattern might have a significant impact on delay. By and large, arrivals tended to be greater than random, with a few cases of random behavior. Departure counts were similarly analyzed and, as expected, tended to be uniformly distributed.

Nonoccurrence (no train present) field studies were conducted at two of the crossings by using a radar speed gun. Studied were free-flow approach speeds to the crossings and minimum speeds in traversing the crossing. The simple method used was in part predicated on earlier research that used more sophisticated methods (9). Generally, both approach and crossing speeds could be roughly approximated by the normal distribution. These occurrence and nonoccurrence field studies were to serve as the empirical basis of grade-crossing models to be developed.

GRADE-CROSSING MODELS

Occurrence-Delay Model

Although useful, literature on delays at traffic signals (10) is not directly applicable to the case of grade-crossing delays. The literature does suggest problem analysis by using computer simulation. With simulation, detailed vehicle behavior under various crossing conditions can be easily studied.

To treat grade-crossing delays, a microscopic event-scan simulation model has been developed. Written in FORTRAN, the model tracks individual vehicles (automobiles, light trucks, and heavy trucks) to and through grade-crossing blockages, tallying delays and stops along the way.

Due to the variable peaking characteristics of highway vehicles versus trains, time-of-day varia-

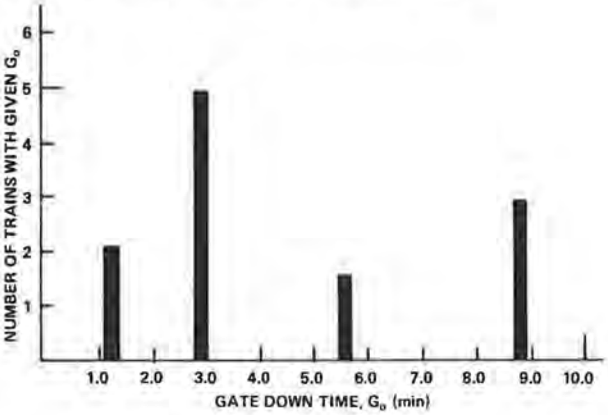
Table 1. Summary of study site characteristics.

		No. of Moving Lanes		Speed (km/h)								
				Avg. Vehicle Approach		Crossing						
Crossing	1980 Average Daily Traffic (ADT)	N	S	N	S	N	S	Crossing Condition	No. of Railroad Tracks	No. of Trains per Day[a]	Total Gate Time Down (min)	Comment
Columbia/B&OCT	10 500	2	2	48	48	16	16	Very rough	5	45	130	Alternate routes available, but tracks cannot be avoided
Kennedy/CR	18 500	2	2	58	58	37	37	Rough	1	14	40	No alternate routes available
Hohman/B&OCT	10 000	1	1	40	40	29	29	Fairly smooth	2	42	126	Alternate routes available, but tracks cannot be avoided
Sohl/CR	6 500	2	2	40[b]	40[b]	19	23	Very rough	2	28	70	Adjacent to signalized intersection; "escape" route available–grade separation 805 m east

Note: N = northbound, S = southbound.

[a] All freight. [b] Approach speed for vehicles not stopped by traffic signal.

Figure 1. Sample train histogram—one time-of-day period.



tions are explicitly recognized. For highway vehicles, up to 12 time-of-day periods are covered for each travel direction. For trains, up to six time-of-day periods are covered.

Train behavior is treated by a histogram approximation, based on the expected numbers of trains by train blockage time (Figure 1). Train speed is associated with the gate down time of a histogram point. To investigate the impact of increasing train speed, for example, the associated gate down time would be appropriately reduced. The railroads operating over the grade crossings provided the data to formulate the histograms (11).

Arrivals, departures, and speeds of highway vehicles are all treated by Monte Carlo techniques. Vehicle approach speeds to a train occurrence are treated as being normally distributed, while crossing speeds are based on fundamental flow relations.

The results of an occurrence simulation are detailed performance measures summed over individual vehicles, such as total delay time, idling time, speed cycles, and slow-speed time. To ensure statistical accuracy and to identify variability in behavior, each train occurrence is repeated a user-specified number of times and final results are averaged. Performance measures summed over all gate down times in a time period are stored for later conversion into highway-user effects.

After extensive debugging to verify proper processing, the model was run on train occurrences observed in the field studies. The results indicate that the model replicates field delay well as long as good input data are provided.

Nonoccurrence Model

It seems appropriate to characterize nonoccurrence behavior in terms of statistical variations around average speed values. Both approach speed and crossing (minimum) speed would follow regular patterns of variation. By assuming final resumed speed to be identical to approach speed, nonoccurrence behavior can then be treated in terms of speed cycles.

The nonoccurrence model developed follows the principles just outlined. Approach and crossing speeds are assumed to be normally distributed around their mean values. The assumption of final speed equal to approach speed is in part due to effect evaluation data structured in this way (12). Approach and crossing speeds of individual vehicles are assumed to be independent, which is in line with earlier research (9). Last, speed combinations are constrained so that crossing speed is less than or equal to approach speed, as is generally expected.

Time lost in slowing at grade crossings with no train present is not included in this model. The addition of a few seconds travel time to an individual vehicle trip is not felt to merit treatment for value of time (VOT) lost.

This analytic treatment of speed behavior is executed on the computer and applies to all vehicles not affected by train blockages. The results are arrays of speed cycles generated by vehicle type (automobile, light truck, and heavy truck). As with occurrence performance measures, speed-cycle arrays are stored for later conversion into highway-user effects.

Validation of the nonoccurrence model consisted of basic program check-out only. The underlying theory was assumed to be true, since no data base was available for extensive validation.

Effect Evaluation Programs

Once the basic grade-crossing models were developed, effect evaluation programs were written. These programs use the most current data for converting vehicle slowing, stopping, idling, and delay into user costs, direct energy consumption, and pollutant emissions (12;13, Appendix B). In the case of highway-user costs, the operating costs cover the following cost components: fuel, oil, tire wear, vehicle maintenance, and vehicle depreciation.

Table 2. Daily vehicle delay at study sites, 1980.

Crossing	ADT	Time Delay (h)	Vehicles Delayed	Percentage of ADT Delayed
Columbia/B&OCT				
Northbound		26.4	762	
Southbound		19.5	565	
Total	10 500	45.9	1327	13
Kennedy/CR				
Northbound		9.1	353	
Southbound		7.8	315	
Total	18 500	16.9	668	4
Hohman/B&OCT				
Northbound		17.7	530	
Southbound		17.3	519	
Total	10 000	35.0	1049	10
All three crossings	39 000	97.8	3044	8

VOT follows guidelines given in a manual by the American Association of State Highway and Transportation Officials (12). The monetary value is taken to vary by both trip purpose and length of delay and is applied to occurrence delays only. All costs are in 1980 dollars but can be updated at program execution time.

The effect evaluation programs perform straightforward computations, applying the basic effect conversion data to the stored arrays of performance measures. Since the effect conversion data are recorded in convenient tabular form, they can be easily updated as more current information becomes available (e.g., changes in vehicle operating costs with changes in vehicle design).

Program validation consisted of check-out of the computational procedures only. The critical element is the validity of the effect conversion data.

MODEL APPLICATION TO STUDY SITES

With traffic, geometric, and train operating data collected in the field studies plus data available from the Hammond Railroad Relocation and Consolidation Project (11), the three isolated grade-crossing sites were analyzed with the models. Delay, cost, direct energy, and pollutant emission results are discussed in turn.

Delay

Delay results are given in Table 2. Although only daily totals are shown, each crossing was typically analyzed in six time-of-day periods for each travel direction. The maximum volume delayed in any one period and direction analyzed is at Columbia/B&OCT, with about one-quarter of all vehicles delayed in a southbound evening peak period. This is a reasonable result; if the fraction were larger, many drivers would divert to other travel routes.

Overall, most delay is estimated to occur at Columbia/B&OCT, with nearly 46 h of vehicle delay/average weekday, which affects 1300 vehicles out of the average daily traffic (ADT), or 13 percent. This particular crossing is blocked for more than 2 h/day by train activity. In contrast, only 4 percent of the vehicles at Kennedy/CR are delayed for about 17 h/day. The result reflects a much lower level of train activity.

If vehicles delayed were estimated by simply the percentage of time each crossing is blocked times the ADT, the respective numbers of vehicles delayed by crossing would be only 950, 510, and 880--all underestimates. This point illustrates that delay is sensitive to the relative time distributions of highway and train traffic.

Highway-User Costs

The corresponding highway-user costs are presented in Table 3. The added excess cost per day is in the range of $100-$300/crossing. On average, the excess is equivalent to drivers having to travel about an additional 0.20 km (0.125 mile) of roadway for each crossing.

Nonoccurrence costs (slowing only with no train present) dominate occurrence costs in the ratio of 2.3:1. This result will be discussed further.

Between occurrence costs, operating costs dominate VOT costs in the ratio of about 2:1. The result partly reflects the nature of the VOT formulation, a point to be further discussed also.

The daily costs can be annualized and are presented in 1980 dollars below:

	Cost ($000s)			
	Occurrence		Nonoccurrence	
Crossing	Operating	VOT	Operating	Total
Columbia/B&OCT	20	13	56	89
Kennedy/CR	10	4	78	92
Hohman/B&OCT	13	7	18	38
Total	43	24	152	219

Annual costs are further compared with accident costs in Table 4. Without going into detail, accident costs are made up of quantifiable items only, which include property damage, medical costs, public service costs, and other costs (11). There is no assigned value for human pain and suffering, however. It is believed that monetarization of human pain and suffering is pure conjecture and should not be included in a benefit/cost analysis.

Predicted accident costs are based on areawide accident rates. The closeness of the predicted-rate cost and the actual-rate cost is fortuitous. For these three crossings, nonaccident costs dominate accident costs by the ratio of nearly 4:1. If the crossings were perfectly smooth with no slowing costs, the nonaccident and accident costs would be about the same.

Direct Energy

Table 5 presents the direct energy results for automobiles only. Fuel-consumption data for trucks are judged to be lacking in accuracy for use here (12). It is estimated that direct energy would be 10-20 percent higher if truck fuel consumption was included.

The table indicates a relative breakdown between occurrence and nonoccurrence energy about the same as that for cost. Annualizing and converting to barrels-of-oil equivalent (BOE) yields the following:

	Annual BOE		
Crossing	Occurrence	Nonoccurrence	Total
Columbia/B&OCT	245	343	588
Kennedy/CR	105	533	638
Hohman/B&OCT	182	161	343
Total	532	1037	1569

On the whole, these three crossings lead to excess consumption of about 1600 BOE annually, with about one-third due to train occurrences and two-thirds due to vehicle slowing when no train is present.

Pollutant Emissions

Pollutant emissions are also presented in Table 5, summed over both occurrences and nonoccurrences. Included are emissions from all types of vehicles. On an annual basis, these three crossings lead to excess emission of 49 000 kg (54 tons) of carbon monoxide and 7300 kg (8 tons) of hydrocarbons. Nonoccurrence slowing accounts for 75 percent of the excess carbon monoxide and 80 percent of the excess hydrocarbons.

SENSITIVITY ANALYSIS

After completion of initial model runs, the next step was to test the sensitivity of the results to input parameters. An additional goal was to investigate how the study methods might be generalized.

Table 3. Daily highway-user costs at study sites, 1980.

Crossing	Cost (1980 $)			
	Occurrence		Nonoccurence	
	Vehicle Operating	VOT	Vehicle Operating	Total
Columbia/B&OCT				
Northbound	35	22	98	155
Southbound	27	17	74	118
Total	62	39	172	273
Kennedy/CR				
Northbound	17	8	125	150
Southbound	14	4	115	133
Total	31	12	240	283
Hohman/B&OCT				
Northbound	20	11	28	59
Southbound	19	10	27	56
Total	39	21	55	115
All three crossings	132	72	467	671

Table 4. Annual accident versus nonaccident costs at study sites, 1980.

Crossing	Costs (1980 $)				
	Accident		Nonaccident		
	Predicted[a]	Actual[b]	Occurrence	Nonoccurrence	Total
Columbia/B&OCT	19 700	500	33 000	56 000	89 000
Kennedy/CR	18 400	38 400	14 000	78 000	92 000
Hohman/B&OCT	19 700	19 200	20 000	18 000	38 000
All three crossings	57 800	58 100	67 000	152 000	219 000

[a] Predicted accident cost is based on areawide accident rates at more than 350 grade crossings (11).

[b] Accident costs based on actual accidents (1974-1976).

Table 5. Daily direct energy (for automobile traffic only) and emissions at study sites.

Crossing	Direct Energy (kW-h)		Pollutant Emissions (kg)	
	Occurrence	Nonoccurrence	Carbon Monoxide	Hydrocarbon
Columbia/B&OCT				
Northbound	730	1060	27	4
Southbound	560	760	20	3
Total	1290	1820	47	7
Kennedy/CR				
Northbound	290	1400	39	7
Southbound	260	1420	39	6
Total	550	2820	78	13
Hohman/B&OCT				
Northbound	470	440	13	1
Southbound	470	440	13	1
Total	940	880	26	2
All three crossings	2780	5520	151	22

Note: 1 kW-h = 3413 British thermal units (BTUs), and 1 kg = 2.2 lb.

Occurrence Analysis Method

The most important occurrence sensitivity analysis deals with the possibility of simplifying the analysis method. A special study of this was made as follows.

An important finding from initial model runs is that, regardless of other conditions, the average delay per vehicle is constant and is equal to one-half of the blockage time. The most general assumption about vehicle arrivals is that they occur randomly. Last, it is reasonable to assume that vehicle departures from an occurrence are uniformly distributed.

By applying these factors, vehicle delay at train occurrences can be analytically computed by using the Borel-Tanner probability distribution (14). The major result of this analysis is that expected total delay is the same as that obtained by assuming both arrivals and departures to be uniformly distributed.

In the case of the long blockage time usually associated with train occurrences, the random arrival assumption appears particularly appropriate. With this general assumption, occurrence delay can then be easily predicted by the following equations (8):

$$\text{Number of vehicles delayed} = (G_o \cdot q)/(1 - y) \tag{1}$$

$$\text{Total time delay} = (G_o^2 \cdot q)/2 \cdot (1 - y) \tag{2}$$

where

G_o = flow blockage time (gate down time) (min),
q = vehicle arrival rate (vehicles/min), and
y = flow ratio, equal to q divided by the vehicle departure rate with the gates up (saturation-flow rate) (vehicles/min).

These equations can be used to predict delay in most real-world situations. The most important feature of such application is to use as accurate traffic and train data as possible, properly segregated into appropriate time-of-day periods. A following section presents the results of a large-scale analysis on 385 grade crossings by using this full-uniformity model.

The simulation-delay model described earlier should be used where particularly good field data are available that indicate high flow ratios in peak study periods (>0.50) with nonrandom arrivals. In practice, the number of grade crossings fitting these criteria probably is small.

Other Occurrence Studies

Other sensitivity analyses have been conducted by using the simulation model. The first of these indicates that even with nonrandom arrivals, vehicle delay often approximates to the full-uniformity delay of above.

Analysis of variation in delay time over simulation repeats has been conducted. As expected, the total delay coefficient of variation (σ/μ) decreases with increased blockage time. Departure pattern in relation to delay has been studied. The effect is found to be negligible, also as expected.

Some cost effects have also been studied. The major result here is the VOT costs make up a much higher percentage of the total highway-user costs than in the initial runs on the three study sites: 70-80 percent, as opposed to 35 percent. This result is apparently due to the use of a higher percentage truck component plus the nature of the VOT formulation. This formulation sees a step jump in VOT for delays exceeding 5 min. Since this analysis includes two gate down times greater than 5 min, while the earlier analyses did not, VOT costs are higher. The point is that VOT costs must be fully documented to provide meaningful results.

Nonoccurrences

The major nonoccurrence analysis focuses on the use of statistical variation in vehicle speeds as opposed to fixed average approach and crossing speeds. The results indicate that introduction of speed variation around the averages has a significant impact: highway-user costs increase from 5 to 70 percent. The greatest differences occur when average approach speed and average crossing speed are close.

What is also clear from the runs as well is that most of the increased cost is related to the redistribution procedure used in the analysis. This procedure evenly redistributes infeasible combinations of approach and crossing speed so that crossing speed is always less than or equal to approach speed. Based on this study and engineering judgment, it is estimated that the procedure is valid as long as average approach speed exceeds average crossing speed by at least 8 km/h (5 mph).

All of these nonoccurrence studies have also been evaluated with respect to direct energy consumption. Generally speaking, the direct energy impact is smaller than that of costs, averaging about four-fifths the cost variation under like conditions.

Traffic Diversions

An important aspect of grade-crossing behavior not yet discussed is traffic diversions away from train occurrences. In the Hammond area, such diversions were observed frequently in the field studies, which affects delay behavior a good deal. The question then arises as how best to treat this phenomenon in delay analysis.

Unfortunately, there is no easy answer to this question. Short of network modeling with fully calibrated route-assignment algorithms, each crossing must be treated on its own merits. For example, one crossing might lie near an existing parallel route that is grade separated. Drivers might routinely divert to the grade-separated route during train occurrences, which makes estimation of adverse effects of the crossing fairly simple. At the other extreme, another crossing might be miles from the nearest escape route, such that diverting drivers might find themselves worse off than if they just stayed put. In this case, effect estimation becomes complex and difficult to quantify.

The situation with respect to the three study sites considered was much closer to the latter case, i.e., no easy escape routes. In the analyses, no effort was made to adjust occurrence traffic volumes for possible diversions. The delay estimates thus generated were taken as a lower limit on adverse effects of the crossings. Other study sites, no doubt, would merit other treatments.

Table 6. Highway-user effects of 385 grade crossings in northwest Indiana, 1980.

Effect	Total (000s)	Average per Crossing (000s)
Delay		
No. of vehicles	48 950[a]	127
Vehicle hours	1 500	3.9
Cost (1980 $)		
Occurrence		
Operating	2 369	6.2
VOT	2 347	6.1
Total	4 716	12.3
Nonoccurrence	7 582	19.7
Total	12 298	32.0
Energy (kW-h)		
Occurrence	40 554	105.3
Nonoccurrence	88 737	230.5
Total	129 291	335.8
Pollutant emissions (kg)		
Carbon monoxide	2 665	6.9
Hydrocarbons	405	1.1
Accident costs (1980 $)		
Vehicle-train	3 396	8.8
Vehicle-vehicle	188	0.5
Vehicle-property	44	0.1
Total	3 628	9.4

Note: 1 kW-h = 3413 BTUs, and 1 kg = 2.2 lb.

[a] Five percent of total grade-crossing traffic delayed.

APPLICATION OF FULL-UNIFORMITY DELAY MODEL

It has been seen that for most practical applications, the full-uniformity delay model should suffice. This model has been used in a major railroad relocation study, as summarized below (11).

The study area covered 385 grade crossings in Lake and Porter Counties in northwest Indiana, which includes the cities of Hammond, Gary, East Chicago, and Whiting. Specifically considered in a preliminary stage were six plans for rail relocation, which were later narrowed down to three. Three analysis years that cover a 20-year planning horizon were studied.

To analyze and compare alternatives, the full-uniformity model was used to estimate highway-user delay, costs, direct energy consumption, and pollutant emissions associated with train occurrences. Nonoccurrence behavior was treated by using fixed average speeds (approach and crossing). This relocation study preceded the research covered in this paper and thus did not include statistical variation in vehicle speeds.

Application of the model included segregation of vehicle and train traffic into separate time-of-day periods, which required compilation of extensive highway traffic and train traffic data from a number of sources. Train behavior was modeled by using the same histogram approach described earlier. The problem of traffic diversions away from congested crossings, which occurred as vehicle volumes grew over time, was treated by manually reassigning traffic to parallel routes. Most of the many occurrence and nonoccurrence computations were carried out in a computer program.

Table 6 summarizes the highway-user effects over all 385 grade crossings for the 1980 existing condition. Estimated accident costs are included in the table.

The estimated 50 million vehicles delayed/year incurred added highway-user costs of about $12.3 million due to the grade crossings. The crossings led to the excess consumption of about 129 million kW-h of energy (76 000 BOE). Excess emissions were estimated to be 2 665 000 kg (3000 tons) of carbon monoxide and 405 000 kg (450 tons) of hydrocarbons. Finally, annual accident costs were placed at $3.6 million, with most of this due to vehicle-train accidents.

Relations between cost components can be compared to those seen earlier. For the 385 grade crossings, nonaccident costs dominated accident costs by the ratio of 3.4:1 versus 3.8:1 for the three study sites. Nonoccurrence costs for the 385 crossings dominated occurrence costs in the ratio of 1.6:1

versus 2.3:1 for the three study sites. The difference, in part, is probably due to the use of statistical variation in speed behavior for the three study sites, as discussed earlier.

Finally, occurrence costs for the 385 crossings split about evenly between operating and VOT components, versus a ratio of 1.8:1 for the three study sites. The difference may be due to a higher number of delays that exceed 5 min for the 385 crossings, thus leading to higher VOT costs.

Based on the relocation study, the project steering committee has recommended the relocation of 13.5 km (8.4 miles) of a diagonal rail line through Hammond, plus the construction of six grade-separation structures (11). Currently, two of the grade-separation structures are under design and slated for construction in the near future by using federal monies. Preliminary engineering of the rail relocation also will begin soon. Justification for the structures and the relocation rest heavily on the techniques discussed here.

DISCUSSION OF RESULTS

This work has focused attention on interactions and effects of rail-highway grade crossings with respect to highway users. Although initially theoretical, the work has yielded practical techniques. For analyzing train occurrences, the full-uniformity delay model is recommended. For analysis of nonoccurrence slowing, a method based on observed variation in vehicle speeds is recommended.

These methods should find application at a few different levels. On a large scale, they can be used to analyze and compare alternative methods of rail relocation and consolidation. Particularly in this day of increased economic accountability, it is desirable to get as good an evaluation of alternatives as possible. An example application has just been discussed.

On a smaller scale, the methods can help evaluate individual sites considered for improvement. From a local point of view, the insight gained may provide the needed justification to obtain local, state, or federal funds, or may identify where to spend limited funds. From a railroad point of view, the methods might be used to enlist local support for grade-crossing improvements. By recognizing the dollar-and-cent costs of grade crossings, a better spirit of cooperation and communication between railroads and local communities might be achieved.

Although the required computations could be done by hand, it has been found more convenient to computerize the methods. A computer package titled HUGC has been developed, which provides computational ease and ready data manipulation. It has been applied in a few study situations.

Overall, these methods should be combined with techniques for analyzing other aspects of grade crossings and of railroads in general. A more comprehensive framework for first quantifying and then minimizing adverse impacts of railroads can thus be established. The importance of such a framework is becoming clearer every day. It is, for example, in everyone's best interests to minimize the disruption that 100-car coal trains bring to western communities as we attempt to improve the energy situation.

More generally, revitalization of this country's rail system is seen as a major transportation issue as energy and other resource constraints close in on society. It is hoped that the methods discussed here can play some role in the task of expending limited transportation resources where they will do the most good.

FURTHER RESEARCH

From a variety of research needs that surfaced from this work, the following areas are judged to be the most critical. Nonoccurrence behavior at grade crossings has been seen to dominate occurrence behavior frequently. Therefore, more sophisticated speed studies should be conducted than were possible here at crossings fully instrumented with speed traps. Statistical speed distributions, time-of-day variations, and correlations between approach and traverse speed are some of the aspects to be studied.

For occurrence behavior, the question of capacity restraint and route assignment as they relate to traffic diversions needs to be addressed systematically. Another major concern here is treatment of nonisolated grade crossings (i.e., those significantly influenced by other road system bottlenecks such as traffic signals). Computer models for handling the case where a grade crossing and a traffic signal are adjacent to one another have been developed (8). In these models, the separate effects of the traffic signal and the grade crossing are considered. Further research by using these models may be conducted in the future.

The effect evaluations discussed here generally relied on cost, energy, and emissions data that were old, hypothetical, or not well documented. On-going work is needed to keep effect data up-to-date, especially in view of changing vehicle technology.

SUMMARY AND CONCLUSIONS

Due to a lack of prior work, basic research into the nonaccident effects of rail-highway grade crossings on highway users has been conducted. Methods of analysis for isolated grade crossings (i.e., those not affected by other highway system bottlenecks) were first developed to study highway-user effects in detail. The methods consisted of computer simulation and analytic techniques that estimated the following highway-user effects: delay, cost, direct energy consumption, and pollutant emissions. The methods were validated to the extent possible.

Three study sites were analyzed by using the methods, and the total excess effects due to the grade crossings were estimated to be in 1980:

1. Vehicle hours of delay--31 850;
2. Highway-user costs--$219 000;
3. Direct energy consumption (automobiles only)--1580 BOE;
4. Carbon monoxide--49 000 kg (54 tons); and
5. Hydrocarbon emissions--7300 kg (8 tons).

Nonoccurrence costs (vehicle slowing when no train is present) dominated occurrence costs (train present) in the ratio of 2.3:1. Between occurrence costs, vehicle operating cost dominated VOT cost by the ratio of 1.8:1. Nonaccident costs were then compared with accident costs, with the result that nonaccident costs dominated accident costs by the ratio of 3.8:1.

With respect to this last result, it must be emphasized that safety at grade crossings is not readily convertible into dollars and cents. Crossing safety is an aspect that should be evaluated from the outset on its own terms.

Following initial model runs, sensitivity analyses with respect to the methods and parameters were conducted. The first such analysis showed that if the general assumption of random vehicle arrivals could be made, occurrence delay estimation could be greatly simplified. It is recommended that in most real-world studies, a simple full-uniformity model be used. The most important aspect in applying this full-uniformity model is to use as accurate vehicle and train traffic data as possible, being mindful of the different peaking characteristics of the two modes.

Regarding nonoccurrence behavior, the method of treatment originally developed is recommended for further applications. The method treats vehicle speed behavior in terms of statistical variations around average approach and crossing speeds, with crossing speed always less than or equal to approach speed. It is important that accurate speed data be input to the model for good results. Also, it would be desirable to conduct more comprehensive speed studies than were possible here, at grade crossings fully instrumented with speed traps. These speed studies should provide final verification of the recommended method.

One more point is made with respect to nonoccurrence costs. The consistently high value of this effect indicates that installation of a smooth-surface crossing in general is cost effective. The typical $50 000-$100 000 capital investment pays for itself in a few years at many well-traveled crossings. The Federal Highway Administration program in support of such installations has been well-justified [Rail/Highway Crossings (Safety) Program, P.L. 93-87, Section 203].

Traffic diversions away from train occurrences are seen as a basic complication to analysis, with no hard-and-fast solutions. Each crossing must be considered on its own merits.

A sample application of a large-scale analysis was presented by using techniques similar to those recommended here for general use. The application covered alternatives for rail relocation in northwest Indiana, which encompassed more than 380 grade crossings. As a result of the analysis, two grade-separation structures are currently under design and preliminary engineering of rail relocation will start soon.

Based on this research, a computer model has been developed that uses the recommended methods of analysis. The model has been used in a few applications.

Proper evaluation of railroad impacts on their environment is an important transportation task. Evaluation of alternatives is required for a variety of activities, which includes relocation of rail lines, construction of grade-separation structures, and smaller actions such as smoothing of crossing surfaces. This paper has attempted to contribute to an overall framework of evaluation.

ACKNOWLEDGMENT

I wish to express my appreciation to the Northwestern University Transportation Center Library for allowing unlimited access to its wealth of excellent resources. This work would not have been possible without the support of my employers at Alfred Benesch and Company, who allowed free use of their computer system. I also am indebted to my thesis adviser at the Illinois Institute of Technology (IIT), Moshe Levin. Most of this work was completed as a master's thesis at IIT.

REFERENCES

1. Rail-Highway Crossing Accident/Incident and Inventory Bulletin. U.S. Department of Transportation, No. 1, 1979.
2. A.E. Moon, J. Carter, J. Frank, J.C. Danzig, and B. Whipple. Urban Railroad Relocation: Nature and Magnitude of the Problem. Federal Railroad Administration, Rept. RP-31, Vol. 4, 1975.
3. A.E. Moon, J. Carter, J. Frank, J.C. Danzig, and B. Whipple. Guidebook for Planning to Alleviate Urban Railroad Problems. Federal Railroad Administration, Rept. RP-31, Vol. 3, 1974.
4. T.A. Butcher. Evaluation of Safety Improvements at Highway-Rail Grade Crossings. Purdue Univ., Lafayette, IN, Joint Highway Research Project, Rept. 1, 1973.
5. E.R. Russell. Analysis of Driver Reaction to Warning Devices at a High-Accident Rural Grade Crossing. Purdue Univ., Lafayette, IN, Joint Highway Research Project, Rept. JHRP-74-16, 1974.
6. J.H. Sanders, Jr., G.S. Kolsrud, and W.G. Berger. Human Factors Countermeasures to Improve Highway-Railway Intersection Safety. Federal Railroad Administration, Rept. DOT-HS-800 888, 1973.
7. Railroad-Highway Grade Crossing Handbook. Office of Engineering, Technology Sharing, FHWA, Rept. TS-78-214, 1978.
8. J.L. Powell. Nonaccident Effects of Rail-Highway Grade Crossings by Computer Simulation. Illinois Institute of Technology, Chicago, M.S. thesis, 1980.
9. G.J.S. Wilde, L.J. Cake, and M.B. McCarthy. An Observational Study of Driver Behavior at Signalized Railroad Crossings. Canadian Institute of Guided Ground Transport, Kingston, Ontario, Rept. 75-16, 1975.
10. R.E. Allsop. Delay at a Fixed Time Traffic Signal--Part 1: Theoretical Analysis. Transportation Science, Vol. 6, No. 3, 1972, pp. 260-285.
11. Alfred Benesch and Company. Hammond Railroad Relocation and Consolidation Project, Final Environmental Impact Statement. FHWA, Rept. FHWA-IND-EIS-79-02-F, 1980.
12. A Manual on User Benefit Analysis of Highway and Bus Transit Improvements, 1977. AASHTO, Washington, DC, 1978.
13. Alfred Benesch and Company. Appendices to Hammond Railroad Relocation and Consolidation Project, Final Environmental Impact Statement. FHWA, Rept. FHWA-IND-EIS-79-02-F, 1980.
14. D.L. Gerlough and M.J. Huber. Traffic Flow Theory. TRB, Special Rept. 165, 1975.

Publication of this paper sponsored by Committee on Railroad-Highway Grade Crossings.