Causal Factors in Railroad-Highway Grade Crossing Accidents

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This study examines the contributing factors of rail-highway grade crossing accidents at crossings that have flashing light or crossbuck warning devices. A conceptual model of driver behavior was adapted to the rail-highway grade crossing situation so that a vehicle-train accident could be characterized in terms of the event sequence that led to the collision and the prevailing conditions that were believed to have contributed significantly to the occurrence of the accident. A total of 79 vehicle-train accidents that occurred in North Carolina and Wisconsin were reconstructed and analyzed for patterns of driver error and contributing factors. The findings revealed that, at crossings that have flashers, the credibility of the warning device is a more important problem than its conspicuity. Lack of credibility occurs because of unnecessarily long warning times. At crossings that have crossbucks, driver failure to recognize the presence or approach of a train was the most-common problem. The principal contributing factors were low driver expectancy of a hazard and inadequate quadrant-sight distance. Potential safety countermeasures were identified based on the contributing factor patterns.

Despite extensive research, differences in opinion still remain regarding the major causes of vehicular accidents at rail-highway grade crossings. Factors frequently considered as major contributors to crossing accidents are (a) inadequate signing and signals, (b) lack of credibility and conspicuity of warning devices, (c) driver inattention or risk-taking, and (d) alcohol

The purpose of this study (1) was to identify patterns of contributing factors for vehicle-train accidents by using a case-study approach. The term contributing factor was used in lieu of causal factor to denote a set of prevailing conditions that, when present, can lead to or be associated with a type of accident. A causal factor would denote that the factor was the cause of the accident and once it was present an accident must occur or, conversely, in its absence an accident would not occur. The scope of the research was limited to crossings that have crossbuck or flashing-light warning devices that had recently experienced a vehicle-train accident. Accidents that involved alcohol or a stalled vehicle were excluded. The presence of alcohol was considered to dominate any other contributing factor. Stalled-vehicle accidents were assumed to be due to a vehicle breakdown rather than to a driver-related error.

RESEARCH APPROACH

A driver behavior model was developed for the rail-highway grade crossing situation so that a vehicle-train accident could be characterized in terms of the event sequence that led to the collision and the prevailing conditions that were believed to have contributed significantly to the occurrence of the accident. The assignment of contributing factors for any given accident required that the operational steps in the driving guidance and control process be specified fully. Fundamentally, an accident occurs because a driver is unable to select an appropriate speed and path through a roadway segment or is unable to successfully carry out that decision. Driver error is not the essential consideration; rather, the prevailing conditions interacted to create the opportunity for driver error. These prevailing conditions can encompass the full range of driver, vehicle, and roadway characteristics.

Driver Behavior Model

A useful model for conceptualizing these behavior relations is one formulated by Michaels (2) and shown in Figure 1. The model depicts the operational steps in the driving guidance and control process in the context of a driver-vehicle-roadway system. The blocks labeled sensory detection, perception, analytic operations, decisionmaking, and control response constitute the basic chain of the driving guidance and control process. A breakdown at any one of these tasks can lead to an accident.

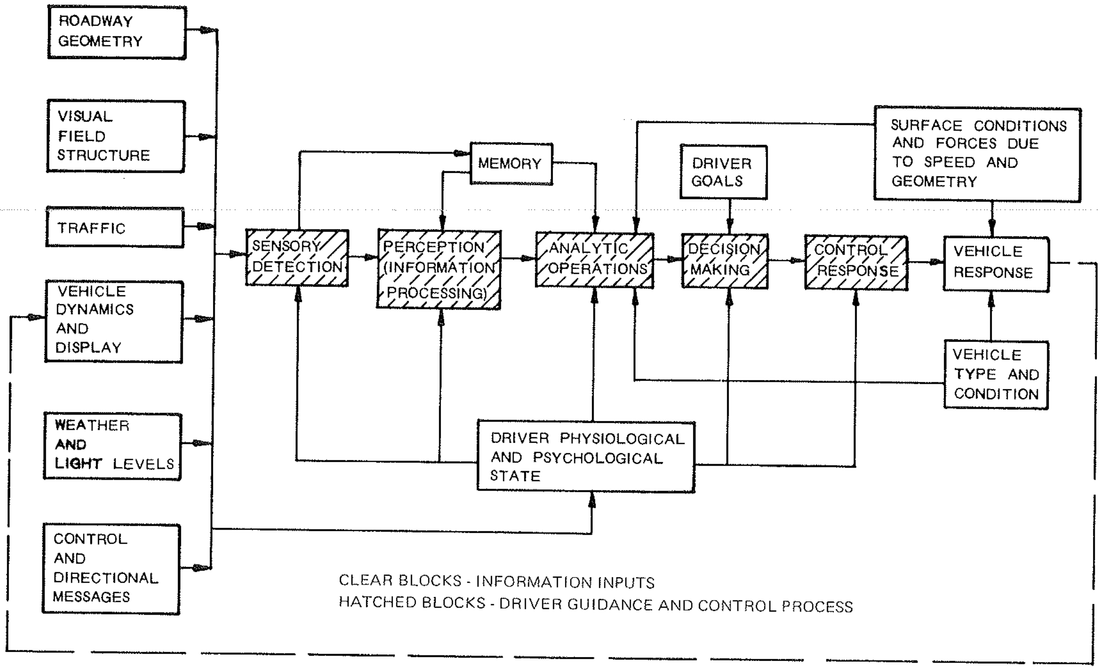
The performance of these tasks is shown to be a function of a variety of information inputs from the driver-vehicle-roadway system. In the context of the rail-highway grade crossing, roadway geometry includes the various design features of the street or highway as well as the crossing itself. Visual field structure refers to the objects, lines, edges, road textures, and contrasts within the driver's visual field. Traffic information includes the velocities and positions of other vehicles, including approaching trains. Information about vehicle response to adjustments in speed and path are transmitted to the driver by means of physical sensations or visual reading of dashboard instruments. Weather and light conditions affect the driving process by altering the available tire-roadway friction as well as the amount of information that can be seen and used for vehicle control.

Traffic control devices, including warning devices at the rail-highway crossing, inform or misinform the driver, depending in part on their conspicuity and credibility. The driver's prior knowledge influences expectancy regarding various rail-highway crossing situations and, therefore, the way in which he or she responds to the hazard presented by the crossing. Vehicle type and condition also influence the response of drivers to hazardous situations. Finally, the driver's own physiological and psychological state will modify the entire guidance and control process.

Possible driver-vehicle-roadway interactions are numerous and complex. If reasonable countermeasures to accidents at grade crossings are to be developed, then the principal interaction patterns that are active in the case of vehicle-train accidents must be identified, categorized, and interpreted in the context of a systematic model of driver behavior. For the purposes of this study, the basic tasks in the driving guidance and control process were aggregated into three elements: recognition, decision, and action.

We hypothesized that the occurrence of a vehicle-train accident was the result of a recognition, decision, or action error. A recognition error was defined as a breakdown in the detection or perception of information necessary to (a) recognize the presence or approach of a train and (b) identify the available actions that would avoid a collision. A decision error was defined as a breakdown in either the analysis of that information or the selection of an appropriate collision-avoidance maneuver. For this type of error, we assumed that the necessary information to perform these tasks has been detected and perceived in sufficient time to make a decision

Figure 1. Operational steps in driver guidance and control.



and complete the maneuver successfully. An action error was defined as the failure to successfully execute what would have been an appropriate collision-avoidance maneuver.

Information-Handling Zones

The evaluation of the possible presence of recognition, decision, or action errors associated with rail-highway crossing accidents required that these basic tasks be considered within the context of a specific set of time-space relations for a vehicle-train encounter. The principles of information-handling zones as defined by positive-guidance concepts (3) were used for this purpose.

The approach to a grade crossing where an accident had occurred was divided into three zones, as illustrated in Figure 2. An area that extended 15 ft on either side of the centerline of the tracks (centerline of outside sets of tracks in the case of a multiple-track crossing) was defined as the hazard zone, or the area in which impact between a vehicle and a train could occur. An area immediately upstream of the hazard zone was defined as the nonrecovery zone. The length of this zone was equivalent to the minimum stopping-sight distance based on the prevailing surface conditions of the roadway and the reconstructed initial approach speed of the vehicle prior to the accident. Located immediately upstream of the nonrecovery zone was the approach zone. Its length was equivalent to the difference between the decision-sight distance (3) for the posted or assumed speed limit and the computed length of the nonrecovery zone.

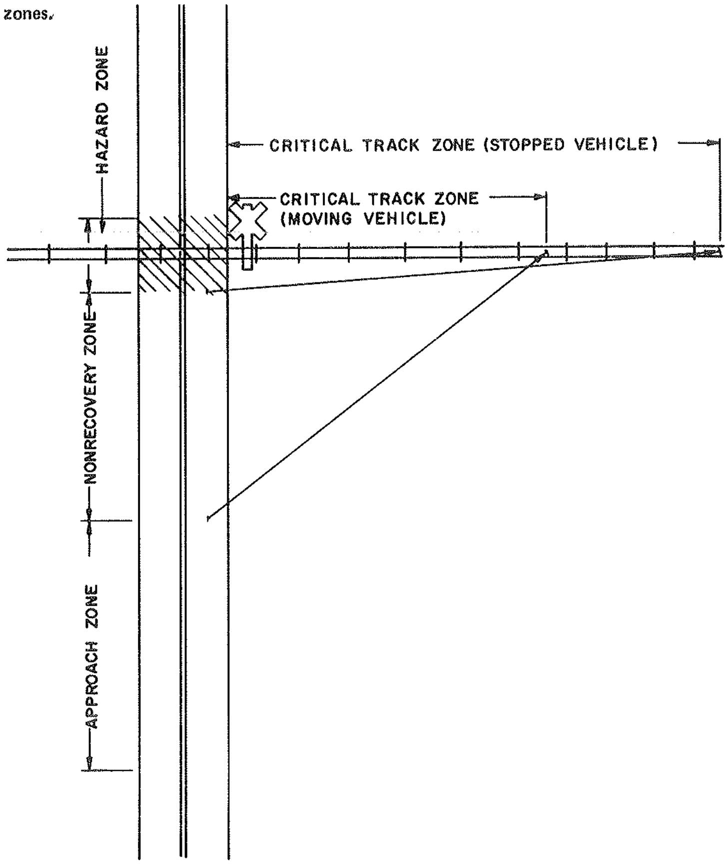
The rail approach on which the involved train was moving was also divided into zones. Two critical zones were defined based on the sight-distance requirements of the involved motorist. The critical track zone for a moving vehicle represented the distance that the involved train would travel during the time required for the subject motor vehicle, approaching at the reconstructed initial speed, to traverse the nonrecovery and hazard zones. The critical moving vehicle track zone, therefore, constituted the minimum desirable quadrant-sight distance under the conditions that prevailed for a given vehicle-train accident. In the context of the previously defined recognition, decision, and action tasks, safe driving performance would require that the driver recognize an activated signal (if present) or the approaching train before he or she entered the nonrecovery zone. If the train had entered the critical track zone by the time the driver reached the beginning of the nonrecovery zone, the appropriate decision would be to stop. If the train had yet to reach the critical zone, the driver could maintain vehicle speed and safely traverse the crossing ahead of the train.

The critical track zone for a vehicle stopped immediately in advance of the hazard zone represented the distance that the involved train would travel during the time required for the motorist to decide to proceed and then to accelerate and traverse the hazard zone. The critical stopped vehicle track zone, therefore, constituted the minimum desirable stop-line sight distance (4) for the conditions associated with a given vehicle-train accident. Safe driving performance would require that a driver who had stopped at the beginning of the hazard zone must recognize whether or not the approaching train was within the critical track zone. If the train is in the critical zone, the appropriate decision would be to wait until the train has passed. If the train has yet to enter the critical zone, the driver could accelerate and traverse the crossing ahead of the train.

Pre-Crash-Event Sequences

The basic recognition, decision, and action steps of the driving guidance and control process were integrated within the information-handling zone framework to produce a set of logic flowcharts that characterize the critical sequence of events that precede a vehicle-train accident. Each unique event sequence was to be examined for predominant patterns of contributing driver-vehicle-roadway factors. These joint patterns of event sequences and con-

Figure 2. Driver information-handling zones.



tributing factors would then serve as the foundation for characterizing the behavorial causes of various types of vehicle-train accidents, the frequency with which these patterns appeared, and potential countermeasures that might be considered.

Figure 3 illustrates the logic flowchart for event sequences and categories of driver error at crossings that have crossbuck warning devices. The chart shows an event sequence that goes from top to bottom. At each recognition, decision, or action point, the alternative paths are identified. The chart, therefore, appears as a tree whose branches terminate with collision between the vehicle and train. Because each path or branch is unique, the driver error that resulted in the accident is identified both by type (recognition, decision, or action), and by a number that references the specific event sequence.

For example, three possible decision errors were defined: D1, D2, and D3. In each case, the driver is believed to have recognized the train from the approach zone. For the D1 and D2 errors, the driver recognizes the train but decides to maintain his or her initial speed and enters the nonrecovery zone. Once within the nonrecovery zone, the driver either decides to attempt to traverse the crossing ahead of the approach train (error D1) or decides to make an emergency stop by placing the vehicle into a skid (error D2). In the case of a D3 error, the driver stops in advance of the hazard zone but decides to traverse the crossing after the approaching train has entered the critical track zone. In each of the above situations, a decision error has been made. The prevailing driver, vehicle, and roadway conditions must then be examined to determine if there is a plausible explanation for the driver's behavior.

In addition to the three types of decision error, Figure 3 illustrates the event sequences for four types of recognition errors and two types of action errors. Figure 4 depicts the similar even sequences and driver errors associated with crossings that have flashing-light warning devices.

DATA COLLECTION

Case-study accidents were selected from Wisconsin and North Carolina because of the completeness and accessibility of police accident reports for 1978 and 1979 vehicle-train accidents. Crossings that had experienced accidents were sorted first by type of warning device (flashing light or crossbuck) and then by county. In Wisconsin, accident sites were only identified for the six contiguous southeastern counties of Milwaukee, Waukesha, Dane, Jefferson, Rock, and Dodge. This selection was made to limit travel time between crossing locations during the field investigations.

The Federal Railroad Administration (FRA) was then contacted to procure the U.S. Department of Transportation-Association of American Railroads crossing inventory information printouts and the FRA rail-highway grade crossing accident-incident reports for each of the accident sites. These reports were subsequently merged with the police accident reports provided by each state. Based on time and resource constraints, approximately 80 accidents were to be selected for reconstruction and causation analysis.

In Wisconsin, a random sample of 22 flashing-light crossings and 14 crossbuck crossings was selected. The 22 flashing-light crossings had 24 accidents during 1978 and 1979. The 14 crossbuck crossings experienced 16 accidents in 1978 and 1979.

In North Carolina, 19 flashing-light crossings

Figure 3. Logic flowchart for driver error at interactions that have crossbuck warning devices.

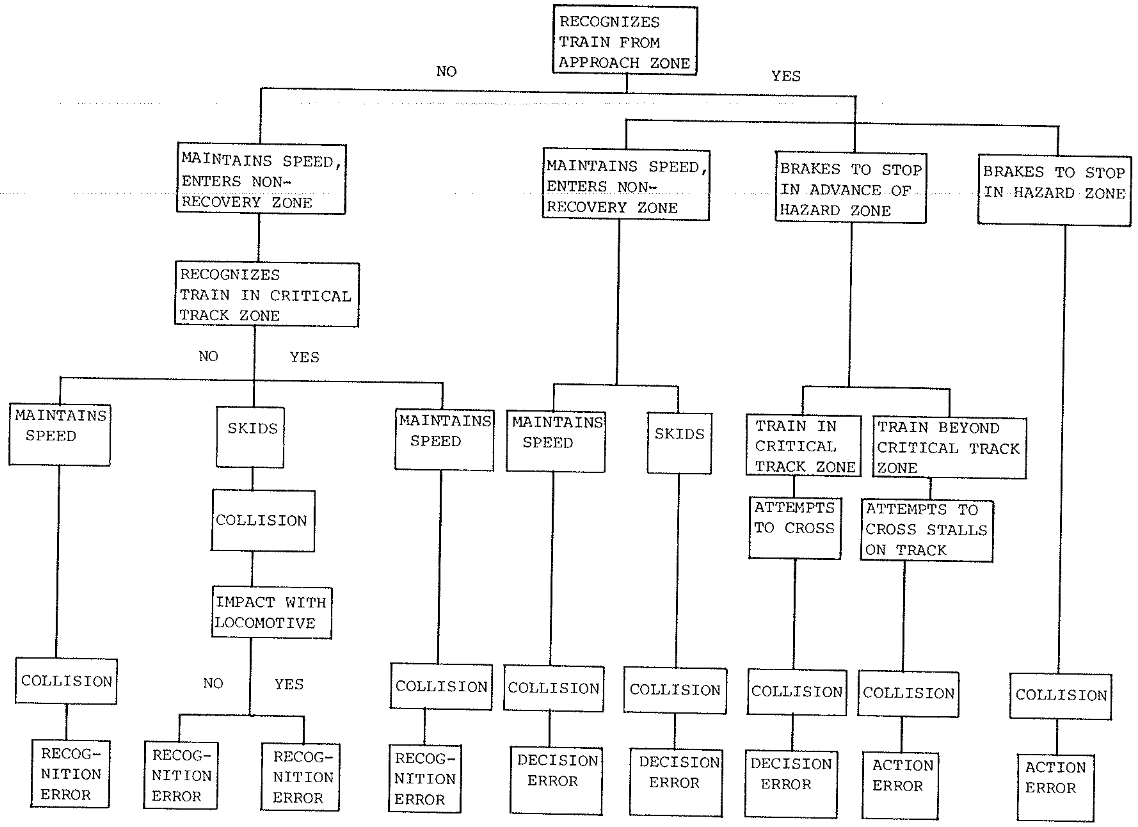
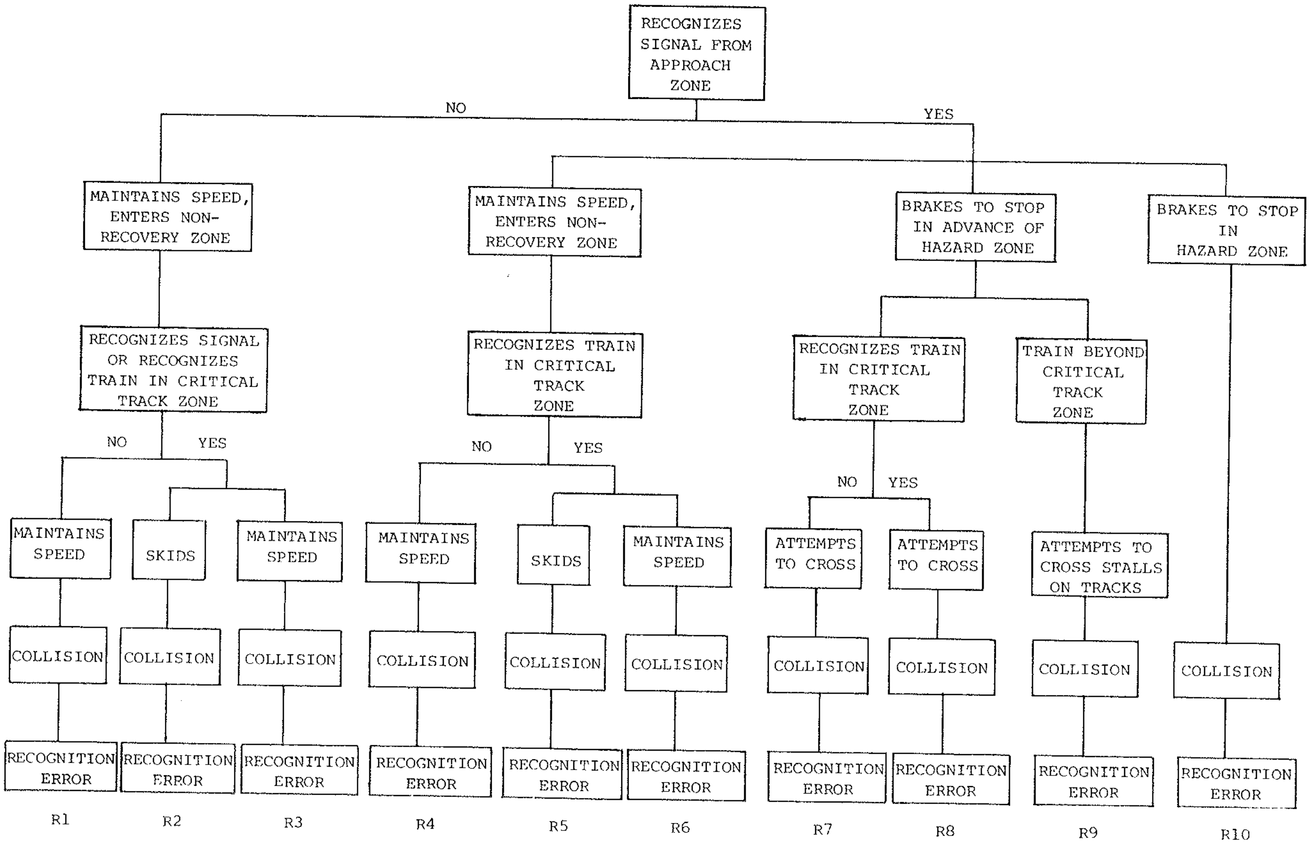


Figure 4. Logic flowchart for driver error at intersections that have flashing-light warning devices.



were chosen on a random basis. A sample of 20 crossbuck sites was then chosen so that these crossings would cluster around the selected flashing-light crossings to minimize travel time during the field studies. Each crossing experienced only one accident during the two-year study period.

Each accident site was then visited to collect data on sight distance, roadway design features, and roadside conditions that might influence driver behavior. In addition, each accident was reconstructed in the context of the event sequence charts shown in Figures 3 and 4. Procedurally, this involved use of skidmark data, reported vehicle and train approach speeds, and the accident report narrative to establish the action taken by the driver and the corresponding positions of the vehicle and train at the critical decision and action points. Notations were also made regarding those factors that might have influenced driver behavior and, therefore, contributed to the cause of the accident.

CONTRIBUTING FACTOR PATTERNS AND COUNTERMEASURES

Each accident was assigned to one of the pre-crash-event sequences shown in Figures 3 and 4. In some cases, an alternative event sequence was defined due to incomplete information about what the driver actually recognized and what decision was made. By using information from the site investigations and accident-reconstruction analyses, the next step was to list the principal factors that were believed to have contributed to the occurrence of each accident. Based on the relative frequency with which various factors were cited, patterns of predominant contributing factors and potential countermeasures were then identified. The results of this process are summarized in Tables 1 and 2 and discussed below. Action errors do not appear because none of the investigated accidents was attributable to this type of error.

Recognition Errors at Crossings That Have Flashers

Of the 43 vehicle-train accidents investigated, 33-44 percent involved some form of driver recognition error, and 53-71 percent were attributed to some form of decision error. The range in frequency is due to uncertainty in assigning type of driver error for some of the accidents.

The information presented in Table 1 reveals that the most-frequent recognition error involves a driver's failure to detect the presence of either the signal or the train. Of the accidents that involved recognition errors, 79-84 percent of the drivers did not detect the signal when they were in the approach zone and had the opportunity to bring their vehicles to a safe stop without placing the vehicle into a skid.

The principal contributing factors for those accidents that involved recognition errors reveal several patterns that have similar potential countermeasures. External distractions that can produce an information overload or divert a motorist's attention from the driving task was a recurring factor. Typical distractions included visual clutter, heavy traffic, adjacent intersections, multiple lanes, rough crossings, and slippery pavement (i.e., wet, snow- or ice-covered). This factor often appeared in combination with the presence of an elderly driver who may have reduced information-processing abilities (error type R1) and with situations in which the signal is obscured from view due to inadequate approach-sight distance or adverse weather conditions (error types R1 and R2). Countermeasures for these types of accidents include increasing signal and possibly train conspicuity. Signal conspicuity might be increased simply by installing additional signals, such as on cantilevers, or by increasing their target value through the use of 12-in roundels or supplementary strobe lights. Although no information was available to determine whether train conspicuity was a problem, the use of roof-mounted strobe lights and high-target-value locomotive paint schemes constitute potentially effective countermeasures.

Recognition error type R4 represents a unique problem where inadequate sight distance is available to drivers of large trucks that have stopped at the crossing. The sight obstruction is created by the combination of an acute crossing angle and a large truck that has restricted visibility to the side and rear. Possible countermeasures to this problem include the use of gates at crossings that have a high percentage of trucks and an acute crossing angle or driver-education materials specifically oriented to truck drivers that would explain precautions that should be taken at this type of grade crossing.

Design Errors at Crossings That Have Flashers

The most-frequent (53-71 percent) type of driver error noted at crossings equipped with flashers was a decision error. In 91-93 percent of these accidents, the driver had recognized the activated signal from the approach zone and either failed to stop or delayed the decision to stop until the vehicle was in the nonrecovery zone. The predominant pattern of contributing factors to these accidents involved extended signal warning time (in excess of 30 s). This factor was usually accompanied by one or more of the following: competing inputs such as multiple tracks and heavy vehicular traffic volume, limited quadrant-sight distance, or inexperienced or elderly drivers.

Warning times in excess of 30 s represented an unnecessarily long advance warning of the approach of a train. Thus, although the activated signal clearly indicated that a train was in the vicinity of the crossing, the train could still be sufficiently far away that it did not constitute an immediate hazard to motorists. The frequently observed pattern of motorists crossing railroad tracks while flashers are operating is believed to be due in large part to extended warning times. Based on the length of the track circuit as measured during the field studies, warning times provided for the accident-involved trains were found to average about 70 s and ranged up to almost 9 min.

The cause of the extended warning times was due primarily to the presence of a low-speed train within a track circuit that had been designed for higher-speed operations. This incompatibility between train speed and track circuit could occur in two ways. First, there might be a wide range in train speeds over the crossing, as could occur near yard areas where switching movements are common. Alternatively, the track circuit may originally have been designed on the basis of high-speed passenger trains that no longer operate over the crossing. Based on the inventory data available for the sample accident sites, the existence of extended warning times was probably a common occurrence at these crossings. This would have an adverse effect on the credibility of the warning device, especially for those motor vehicle operators who tend to drive aggressively and avoid delays or lost time. The presence of heavy traffic flow also creates pressure to maintain speed and avoid stopping.

The frequent presence of limited quadrant-sight distance often effectively delayed the point at which the driver was actually able to observe the train. This tended to compound the extended warning

Table 1. Driver errors, associated contributing factors, and possible countermeasures at crossings that have flashers.

Type of Driver Error[a]	Pre-Crash-Event Sequence	Frequency (%)	Principal Contributing Factors	Possible Countermeasures
R1	Driver does not detect signal or train	12-16	Elderly driver, external distractions, limited quadrant-sight distance	Increase signal and train conspicuity
		7-9	Visibility of signal obscured	Same as R1
R2	Driver recognizes signal or train from nonrecovery zone, attempts to stop	5-7	Visibility of signal obscured due to adverse weather, slippery pavement	Same as R1
R3	Driver recognizes signal or train from nonrecovery zone, does not stop	2-5	Internal distractions; external distractions–multilane highway, heavy traffic, slippery pavement	Same as R1
R4	Driver stops, does not detect train, attempts to cross	7	Limited stop-line sight distance, large vehicle, acute crossing angle, heavy traffic	Install gates, driver education
D1	Driver recognizes signal from approach zone, does not stop, does not detect train	9-14	Extended warning time; competing inputs–multiple tracks, slippery pavement, limited quadrant-sight distance	Relocate beginning of track circuit, provide constant warning time detection, install gates, driver education
		5-7	Inexperienced or elderly driver; competing inputs–heavy traffic, adjacent intersection, multiple tracks; limited quadrant-sight distance	Install gates, driver education
D2	Driver recognizes signal from approach zone, does not stop, recognizes train from nonrecovery zone, attempts to stop	16-19	Extended warning time, limited quadrant-sight distance, truck driver; competing inputs–heavy traffic	Same as D1
D3	Driver recognizes signal from approach zone, does not stop, recognizes train from nonrecovery zone, does not stop	9-14	Extended warning time; competing inputs–low train speed, multiple tracks	Same as D1
		9-12	Extended warning time, inexperienced or elderly driver, limited quadrant-sight distance, competing inputs	Same as D1
D4	Driver recognizes signal from approach zone, brakes to stop, recognizes train, attempts to cross	5	Extended warning time, low train speed, inexperienced driver, limited visibility	Install gates, driver education

[a] See Figure 4.

Table 2. Driver errors, associated contributing factors, and possible countermeasures at crossings that have crossbucks.

Type of Driver Error[a]	Pre-Crash-Event Sequence	Frequency (%)	Principal Contributing Factors	Possible Countermeasures
R1	Driver does not detect train	31-36	Limited quadrant-sight distance, acute crossing angle, low train speed, low expectancy	Remove sight obstructions, additional motorist information, automatic warning device
R2	Train on crossing, driver recognizes train from nonrecovery zone, attempts to stop	19	Limited visibility–darkness, restricted sight distance; inexperienced or elderly driver, slippery pavement, internal distractions	Reflectorization of rolling stock, additional motorist information, crossing illumination
R3	Driver recognizes train from nonrecovery zone, attempts to stop	19	Limited quadrant-sight distance, low expectancy	Same as R1
R4	Driver recognizes train from nonrecovery zone, does not stop	8-11	Limited sight distance, acute crossing angle, darkness	Same as R1
D1	Driver recognizes train from approach zone, does not stop	6-8	Inexperienced or truck driver, slippery pavement	Driver education
D2	Driver recognizes train from approach zone, enters nonrecovery zone, attempts to stop	8	High approach speed, acute crossing angle, low train speed	Driver education
D3	Driver recognizes train from approach zone, brakes to stop, attempts to cross	3	Heavy traffic, multiple lanes, low train speed, limited visibility	Driver education

[a] See Figure 3.

Figure 5. Supplemental advance-warning signs authorized by Minnesota.

time problem because, even though the activated signal indicated that a train was in the vicinity of the crossing, an unnecessarily long warning interval elapsed before the hazard became visible.

Similar countermeasures exist for each of the identified decision errors. The credibility problem created by the extended warning times can be minimized either by adjusting the length of the track circuit to provide an approximately 25-s warning time or by installing constant warning time detection equipment where the range of train operating speeds is large. In some cases, it may be desirable to install gates to remove the driver's option of proceeding across the tracks ahead of the train. Finally, some benefits might be derived over the long run through driver education activities that would emphasize the function and operation of grade-crossing signals and train-detection systems.

Recognition Errors at Crossings That Have Crossbucks

Of the 36 vehicle-train accidents investigated that occurred at crossings that have only standard crossbuck, 77-85 percent involved errors of driver recognition. Of these, 22-25 percent involved late recognition of a train that was already on the crossing.

The predominant contributing factors associated with the recognition of an approaching train was limited quadrant-sight distance due to (a) vegetation, terrain features, or person-made objects or (b) low driver expectancy as reflected by a very low train volume. Low hazard expectancy discourages drivers from actively searching for a train. If a visual search is conducted, the presence of sight obstructions prevents the train from being detected in sufficient time to bring the vehicle to a safe stop.

The principal contributing factor for those accidents that involve a train already on the crossing was limited visibility due to darkness or roadway approaches whose alignment restricted visibility of the crossing from the approach zone. This situation was often compounded by an inexperienced driver, a driver who had reduced visual acuity due to age, or possible internal distractions due to the presence of passengers.

Potential countermeasures for accidents that involve recognition errors associated with an approaching train range from removal of the sight obstructions to the installation of automatic-warning devices. The former is often impractical, and the latter may not be cost effective. An alternative countermeasure would be to provide the motorist with some type of additional information regarding the nature of the hazard and an appropriate approach speed to the crossing. For example, special advance-warning signs (5), as shown in Figure 5, could be used to indicate the presence of limited sight distance, an acute crossing angle, or high-speed trains. These could be supplemented with advisory speed plates that indicate the maximum speed at which adequate quadrant visibility would be available. In some situations, the use of a STOP sign might be warranted (6).

Countermeasures for accidents that involve failure to recognize a train already on the crossing relate principally to improving either the conspicuity of the train or the visibility of the crossing. Reflectorization of railroad rolling stock and illumination of crossings have been studied previously (7,8), and both would appear to offer potentially effective countermeasures for those accidents that occur at night. For those accidents that occur during daylight, the recognition problem was generally created by inadequate visibility of the crossing from the approach zone. Because improvement of the alignment of the roadway is often difficult, special advance-warning signs with advisory speed plates might reduce the likelihood of this type of accident.

Decision Errors at Crossings That Have Crossbucks

Decision errors comprised only 17-19 percent of the accidents investigated that occurred at crossings that have crossbucks. The principal contributing factor patterns were (a) an inexperienced driver or a truck driver traveling on a pavement that is slippery and (b) crossings that have high-volume or high-speed vehicular traffic in combination with low train speeds. Both situations can lead to indecisiveness or risk-taking on the part of the driver due to the desire to avoid unnecessary delay.

Given the typically low train volumes found at this type of crossing and that the train was recognized from the approach zone, the principal countermeasures to this type of accident would appear to be driver-education materials oriented toward better understanding of the hazards posed by grade crossings and the appropriate actions that should be taken once a train has been sighted.

CONCLUSIONS

The results of this study reveal a number of contributing factor patterns associated with driver recognition and decision errors at rail-highway grade crossings. Because of the relatively small sample of vehicle-train accidents that were reconstructed, it is difficult to generalize on the frequency with which any given combination of driver error and principal contributing factors would occur on a nationwide basis. Nevertheless, the results are useful in explaining a behavioral basis for accidents at grade crossings and in identifying potential countermeasures.

Regarding vehicle-train accidents at crossings equipped with flashing-light signals, the study results suggest that the credibility of warning devices is a more-important problem than conspicuity. This is based on the approximately two-to-one ratio in driver decision-to-recognition errors. Lack of credibility occurred principally due to unnecessarily long warning times prior to the actual arrival of the train. Potential countermeasures to the credibility problem include reduction in the length of track circuits to ensure compatibility with existing train operations and installation of constant-warning-time devices where the range in train speeds is large.

For grade crossings that have crossbucks as the single warning device, the study findings revealed that approximately 80 percent of the investigated accidents at these crossings involve driver-recognition errors. The principal contributing factors were lack of quadrant-sight distance and low driver expectancy of the presence of a train. These factors create a behavior pattern in which drivers tend not to look for a train. When an active visual search is made, the train is often hidden from view at the last point where the driver must make the decision to stop. Because removal of sight obstructions and installation of automatic-warning devices are often found to be impractical or not cost effective, a reasonable countermeasure would be to provide the motorist with more-complete information about the nature of the hazard and an appropriate safe approach speed. This could be accomplished with the use of special-message advance-warning signs coupled with speed advisory plates.

Finally, the results of the study indicate that driver-education activities (such as Operation-Lifesaver) should offer an important contribution to the safety problem at grade crossings by making motorists more aware of hazards at grade crossings and how to respond to them. This includes an understanding of the function and operation of the various types of warning devices.

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Pedestrian Cross Flows in Corridors

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An investigation into the nature of pedestrian cross flows in corridors at right angles to one another is described. This study was undertaken by using time-lapse photography to determine the effect of a minor pedestrian flow crossing a major pedestrian flow. Such cross flows of pedestrians are common in major activity centers and in special event transportation systems, such as universities, bus stations, art galleries, museums, and places of entertainment. The results of this study were compared with those obtained from theoretical gap and collision analysis. The comparisons were found to match closely. A design criterion for facilities where cross flows of pedestrians occur is developed based on the data gathered from the films and the theoretical analysis.

This paper describes a study undertaken at Washington State University to examine the characteristics of pedestrian cross flows in corridors, passageways, and hallways and to determine the effect of one pedestrian flow crossing another. Statistical analysis was used to explain these characteristics and to establish a design criterion for facilities where such cross flows of pedestrians occur. Flow characteristics of pedestrians in single channels have been studied and documented by several researchers (1-4). However, investigations into the nature and characteristics of pedestrian cross flows is very limited (5).

Pedestrian crossing movements in this study were observed by using time-lapse photography. Speed-density-flow relations were established from data derived from films. Pedestrian conflicts at cross flows were also observed and analyzed from films. Subsequently, a theoretical gap analysis was used to verify the experimental work. A design criterion based on this investigation is suggested for pedestrian facilities.

PEDESTRIAN CROSS FLOWS

Cross flows of pedestrians are ubiquitous. Corridors, passages, and hallways in schools, booking offices, cinema theaters, art galleries, museums, and places of entertainment are instances where such cross flows are commonly observed. Where pedestrian densities are low, cross flows of pedestrians seldom create problems; but when the pedestrian densities in one or both streams are heavy, the probability of conflicts is high.

Corridors, for instance, dominate the space configuration in buildings. When two corridors cross one another, their users have to use a common area, similar to an uncontrolled highway intersection. Corridors in school and college buildings serve to circulate their users when class schedules require movement of students and faculty on an hourly basis. Conflicts of two pedestrian streams at the junction of two corridors are all too common in such situations. When corridor widths are narrow and the pedestrian concentrations are high in both streams, pedestrian walking speeds, particularly in the minor flow, come to a standstill and queues build up. In the major flow there is evidence of extremely restricted walking speeds, shuffling, and frequent conflicts. One of the reasons for this condition is that corridor widths are usually determined by building codes rather than with respect to pedestrian traffic demand. Even those guidelines and design criteria currently used for corridor design do not take cognizance of cross-flow con-