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Rear-End Collision–Warning System

Design and Evaluation via Simulation

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The design of an innovative rear-end collision-warning system was evaluated for effectiveness. The crash scenario involves a lead vehicle not moving (LVNM) in one lane of a straight, dry, paved arterial road and a following vehicle approaching in the same lane. The LVNM has a rear-facing sensor and is equipped with the rear crash-warning system, which allows the LVNM to flash its brake lights or its center high-mounted stop lamp, warning the following vehicle that it is approaching too rapidly. Because this problem is complex, the scope was narrowed, and it was assumed that the driver of the following vehicle always detected the warning after a response time lag and then applied hard braking. The warning algorithm (i.e., selecting the most appropriate warning distance for each approaching vehicle speed) was designed based on trade-offs to maximize the capability of preventing crashes, reduce the frequency of nuisance alarms, and minimize the severity of crashes. The overall measures of effectiveness of the warning design were then evaluated for a vehicle speed distribution that represented a suburban arterial road. The findings suggest that the warning system should be very effective in preventing crashes. The expected number of nuisance alarms was small, and for the very small percentage of vehicles that would crash, the expected crash severity was negligible. Experimental studies and field operational tests would be required to obtain more accurate numerical values for the design parameters.

The design of an innovative rear-end collision-warning system is addressed and evaluated for effectiveness. For this first analysis of rear collision, we have narrowed the focus to lead-vehicle-not-moving (LVNM) collisions. In the scenario of interest, the LVNM is equipped with a rear-facing sensor that measures the range and speed of the approaching vehicle. The LVNM is assumed to be equipped with a rear crash-warning system that flashes brake lights or the center high-mounted stop lamp when a warning is triggered.

INTRODUCTION

Objectives

The key focus of this study was to model how effective a rear collision-warning system would be in preventing crashes and reducing their severity. Another focus was minimizing false alarm rates, because the potential nuisance of this kind of system may reduce its long-term effectiveness.

The warning algorithm (i.e., selection of the most appropriate warning distance for each following vehicle speed) was designed based on trade-offs among three goals:

- Maximizing the capability of preventing crashes,
- Minimizing the severity of crashes, and
- Reducing the frequency of nuisance alarms.

As such, overall measures of effectiveness were evaluated for the warning design using a speed distribution for an arterial road. Furthermore, sensitivity analyses were conducted on the measures of effectiveness with respect to design parameters.

Background

A crash involving an LVNM may involve three or more vehicles and may actually involve multiple LVNMs. For such crashes, we considered only the initial rear-end collision and ignored subsequent ones. The 1997 General Estimates System (GES) data, the latest available data, included 10,009 rear-end crashes involving LVNMs. Out of these, the most frequent LVNM scenarios and subscenarios are as follows (*1–4*):

- The struck vehicle stopped at or near an intersection (4,274 crashes, 43 percent of total),
  - At or near a signal (2,539 crashes, 25 percent of total),
  - At or near a stop sign (542 crashes, 5 percent of total), or
  - At an intersection with no signals or signs in the travel direction (but possibly and even likely with signals or signs in the crossing directions (111 crashes, 11 percent of total).
- The struck vehicle stopped on a nonfreeway travel lane but was not proximate to any junction (e.g., intersection, ramp, driveway, alley, or railroad crossing). Inference may be made that the vehicle stopped due to traffic congestion or stopped at the end of a queue of vehicles waiting to pass an intersection (3,080 crashes, 31 percent of total).

These scenarios do not include specific road geometry challenges such as curves, because crash data indicate that 75 percent of these crashes occur on straight roads (*4*). One similar finding was that 75 percent of the LVNMs occurred during daylight and the rest occurred under either “Dark and lighted” or “Dark and unlighted” conditions. Although the “Daylight” crashes clearly are more frequent than their “Dark” counterparts, the latter may actually be more likely when the amount of traffic traveling in daylight or darkness is also considered. The same can be said about roadway surface conditions, roadway curvature, roadway grade, and so on.

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Readers are referred to the report by Misener et al. for additional statistical findings on this topic (*4*).

Crash Scenario

The crash scenario involved an LVNM in one lane of a straight, dry, paved arterial road. The following vehicle was approaching in the same lane. The LVNM had a rear-facing sensor that measured range and speed of the approaching vehicle. The LVNM was assumed to be equipped with a rear crash-warning system that flashed brake lights or the center high-mounted stop lamp when a warning was triggered. To reduce complexity, it was assumed that the driver of the following vehicle always detected the warning after the response time lag and then applied hard braking. The issue of warning signal detection was left to future studies.

The scenario included a lead vehicle, temporarily not moving, at the end of a long queue of vehicles at an intersection, at a stop sign, waiting to turn, near a toll plaza, or as a result of traffic congestion ahead. In such situations, flashing hazard lights are typically not used. As evidenced by the number of rear-collision crashes, brake lights are not necessarily effective in preventing such crashes. One could speculate that a rear-facing, radar-based warning system would be able to mitigate or prevent such crashes. Rear-end crashes probably are not simply caused by drivers not looking forward; drivers have been found to look away for mean glance periods of only 1.0 to 1.5 s (*5*). Extending this finding, it is possible to assume that although drivers are looking, they are unalerted and thus require a longer response time before perceiving and reacting to an imminent danger. Furthermore, human perception of closing distance is somewhat poor, and drivers may respond too late to prevent a crash. Thus, a highly salient signal derived from a warning system mounted on the back of a lead vehicle should enable drivers to become aware of crash-imminent situations sooner, hopefully preventing a crash.

Braking versus Steering

One concern was the validity of the assumption that the vast majority of drivers approaching an LVNM brake, rather than steer. A previous literature review revealed that drivers' initial response to an obstacle is to brake (*6*). Once beginning the braking action, some drivers also added a steering component.

This braking-only finding is further emphasized by a study of the GES database, which showed that for the top two LVNM rear-end scenarios, the majority of the drivers made no action prior to impact (78.4 and 68.6 percent) (*2*). A small percentage braked only (15.5 and 25.7 percent), whereas fewer than 4 percent steered only, or braked and steered. These data are inconsistent with experimental studies that show steering maneuvers are more common than 4 percent (*6*). One possible reason is that most of the studies cited by Adams (*6*) were conducted with simulators and on test tracks (*7, 8*)—scenarios with sparse, low-complexity road scenes that may make swerving more acceptable and inviting.

Thus, it is probably safe to assume that most drivers who rear-end collide with an LVNM either brake or make no action. It seems that a very small percentage incorporate a steering component, which indicates the value of a system such as the one we are studying: that unalerted drivers (such as the type we are trying to warn) may not have time to complete the steering movement but that a timely warning can indeed reduce the rate of crashes. This assumption may override the negative value of a nuisance alarm.

INPUT DATA

Factors Affecting the Warning Design

The factors that affect the design of a warning algorithm for the crash scenario considered here are

1. Braking capability of the approaching vehicle (A_d),
2. Response time to warning for the approaching driver (T_d),
3. Comfortable braking rate of the approaching driver (A_{comf}),
4. Speed of the approaching vehicle (V_o),
5. Types of approaching vehicles and their probabilities of occurrence,
6. Mass of the approaching vehicle, and
7. Sensor delay time (T_{sensor}) and brake actuation delay (T_{brake}).

Probability distributions rather than point estimates were used for Factors 1–4. For Factor 5, the approaching vehicle could be a light-duty vehicle (LDV) or a truck. The probabilities of their occurrences were estimated based on data available in the literature (see following sections). For Factor 6, the expected masses of approaching vehicles were computed based on data available in the literature. For Factor 7, the delay times were estimated for sensor and vehicle characteristics.

Design Parameters for LDVs

Emergency Braking Distribution for LDVs

The braking capability distribution for LDVs [automobiles, vans, pickup trucks, and sport utility vehicles (SUVs)] on dry and wet pavements was computed by the National Automated Highway System Consortium (*9*). The braking distribution was derived from vehicle stopping distance data published in *Consumer Reports* and applied to sales figures by vehicle model from *Automotive News Market Data Book.* The distribution contains 2 years of domestic unit sales (1994–1995), and data on maximum braking rates cover approximately 85.5 percent of the 29,870,481 vehicles sold in the United States during those 2 years.

The emergency braking distribution for new LDVs (<4828 km) driven by experienced test drivers was approximately a Gaussian distribution with a mean and standard deviation (for dry pavement test) of $-8.5\ m/s^2$ and $0.6\ m/s^2$, respectively. Derating factors were applied to the data to account for the decreased braking capability of vehicles because of anticipated wear and tear and the fact that typical drivers do not stop their vehicles as quickly as test drivers do.

CAMP (*10*) reported substantially lower values of braking rates than those published in *Consumer Reports,* supporting the validity of derating. Although some of the values suggested a mean A_d value smaller than $5\ m/s^2$, the CAMP authors speculated that drivers would brake harder under real-world conditions. Hence, the nominal value chosen for $A_d\ \mu = -5.5\ m/s^2$) was between the values in the two reports (*9, 10*), and sensitivity studies in each direction were conducted. The standard deviation was fixed at $0.6\ m/s^2$ based on National Automated Highway System Consortium data (*9*). The nominal value for A_d chosen was a conservative estimate, which makes the warning design challenging. However, it is important to realize that a warning design based on this nominal value will improve the effectiveness of preventing crashes only if the actual emergency braking rate for LDVs is higher than this value.

Mass of LDVs

The nominal mass for the stopped vehicle and all other LDVs chosen was 1400 kg. As shown later, because LDVs are able to brake faster than heavy trucks, the probability of a crash with an LDV is very low. This means that even though there is a substantial population of SUVs heavier than 1400 kg, the effect on the crash severity estimates should be negligible.

Design Parameters for Heavy Vehicles

Emergency Braking Distribution for Heavy Vehicles

The majority of heavy vehicles on arterial roads were classified in five categories: loaded straight trucks, empty straight trucks, loaded truck-tractors, empty truck-tractors, and bobtail tractors. Buses were ignored, because their aggregate frequency on arterial roads nationwide is low.

Determining the braking capability for heavy vehicles was much more complex than for LDVs mainly because of widely varying load distributions. Typical emergency braking values for different types of heavy vehicles are summarized in Table 1 (*11*).

Probability of Occurrence of Each Type of Heavy Vehicle

To estimate the effectiveness of a warning design, probabilities of occurrence for each of the above-mentioned heavy vehicle types were needed for arterial roads. For this purpose, data that provided the annual vehicle miles traveled (VMT) by trucks on short haul were used (*12*). For lack of better data, VMT on short haul were assumed to be close to those on arterial roads. About 61 percent of VMT were by straight trucks, 38 percent by truck-tractors, and 1 percent by bobtail tractors.

It also was necessary to estimate the fraction of VMT traveled by empty and loaded straight trucks, and empty and loaded truck-tractors. Such data are difficult to obtain. The Bureau of Economics and Bureau of Operations reported that the percentage of empty trucks on highways for intrastate travel was 33 percent (*13*). Lacking better data, the fraction of VMT on arterial roads was assumed to be 0.33 for empty trucks and 0.67 for loaded trucks. Table 1 is a summary of these data for heavy vehicles.

Mass of Heavy Vehicles

For bobtail tractors, a nominal mass of 9000 kg was used, based on the weight of a tractor used for experimental work at the California Partners for Advanced Transit and Highways Program. Heavy vehicle types have significantly varying masses, and again, such data were not easy to obtain. A nominal value for the mass of each of the heavy vehicle types given above was computed based on data from Oak Ridge National Laboratory (*12*) (listed in Table 1). These data were used to compute the measures of effectiveness of the warning design and the severity of crashes involving heavy vehicles and later were varied parametrically in sensitivity studies.

Comfortable Braking

On the basis of a review of the CAMP report (*10*), a variable, speed-dependent A_{comf} was used for the nominal design. CAMP studies have shown that the CAMP required deceleration parameter (RDP; in *g*) equation for the LVNM case is

$$\text{dec}_{\text{REQ}} = 0.165 + 0.00877 V_o \tag{1}$$

where V_o is the vehicle speed (in meters per second). It has been reported as the 50th percentile for required hard braking over all speeds.

CAMP observed that the values reported by Equation 1 were an upper bound on the 95th percentile for comfortable braking. Assuming that the distribution is normal, 95 percent of this distribution is covered by 2σ from the mean. Thus, the mean values of comfortable braking can be approximated by subtracting 2σ. Converting units (from *g* to m/s^2), subtracting the 2σ, and reversing the sign convention from Equation 1 to represent acceleration rather than deceleration gives

$$\text{Mean } A_{\text{comf}} = -1.617 - (0.0859\, V_o) + 2\sigma \tag{2}$$

This equation provided a reasonable estimate of the mean A_{comf} value as a function of the approaching vehicle's speed. The standard deviation ($\sigma = 0.441\ \text{m/s}^2$) was then approximated from the mean and 95th percentile values reported for three specific speeds: 48, 72, and 97 km/h (*10*). By substituting this value for σ in Equation 2, the final expression for the variable A_{comf} became

TABLE 1 Parameters for Heavy Vehicles

Vehicle	Emergency Braking Rate (m/s^2)	Probability of Vehicle Type	Expected Mass (kg)
Loaded Straight Trucks	- 3.9	0.412	11,000
Empty Straight Trucks	- 3.7	0.203	8,000
Loaded Truck-Tractors	- 4.6	0.252	33,000
Empty Truck-Tractors	- 3.7	0.125	15,000
Bobtail Tractors	-2.9	0.008	9,000

$$\text{Mean } A_{\text{comf}} = -0.735 - (0.0859\, V_o) \quad (3)$$

A_{comf} values derived from Equation 3 were similar to the three specific mean values reported from CAMP experiments (*10*), providing some reassurance regarding the validity of this equation.

Response Time Distribution

A driver's response to a forward stimulus (e.g., brake lights) is broken into two subunits. *Response time* is the sum of *reaction time* (the time from the appearance of the stimulus to the removal of the foot from the accelerator pedal) and *movement time* (time to move the foot from the accelerator pedal to the brake pedal). Some authors use reaction time and response time interchangeably. However, most established researchers use the definitions provided above.

Second, there seems to be a lack of precision in the description of Alerted and Unalerted responses. Because some of the Unalerted findings have been collected in quite different scenarios, we have modified the response time classifications as follows:

- *Alerted*—The driver is aware, ready, and expecting to brake;
- *Surprised*—The driver is in a neutral driving state and is responding with some degree of urgency to a surprising stimulus; or
- *Unalerted*—The driver is in a neutral driving state and is responding to an unsurprising stimulus;

with one potential modifier:

- *Distracted*—The driver is not looking at the road before his or her response. This latency is typically paired only with Surprised or Unalerted.

The driver response distribution was based on data from CAMP (*10*) and Olson and Sivak (*14*); the explicit numbers used were from Olson and Sivak because they accommodate the values reported by the CAMP authors. For example, CAMP indicates that the 95th percentile for response time was 1.52 s. The Surprised response time distribution reported by Olson and Sivak is normal ($\mu = 1.1$; $\sigma = 0.305$ s) and accommodates the CAMP authors' value when the tail of the distribution is examined [$\mu + 2\sigma$ (e.g., 95 percent of the distribution) = 1.71 s]. Unfortunately, the CAMP report does not explicitly specify the mean and the standard deviation for T_d. As such, the nominal T_d was set to the aforementioned Surprised values from Olson and Sivak. Another potential distribution [$\mu = 0.82$ and $\sigma = 0.18$ s (*15*)] was used for sensitivity analyses.

Delay Times

The nominal design included both driver response time and system delay times. A sensor delay time of 0.1 s and a brake delay time of 0.2 s were included. *Sensor delay time* is the time interval between time of data acquisition by the sensor (based on which the warning is issued) and the time at which the warning is issued. *Brake delay time* accounts for the time needed to initiate braking due to pressure buildup after the brake pedal is activated.

The CAMP values for comfortable braking did not include the delay time needed to initiate braking due to pressure buildup (*10*). Therefore, the computations for comfortable braking included an additional 200-ms brake pressure delay time. However, average braking rates, discussed for LDVs and trucks, are computed based on stopping distance experiments. Average braking rates calculated based on such experiments implicitly include the delay time for braking pressure buildup. Therefore, for computations that use the emergency braking values, we did not include an additional 200-ms brake pressure delay time.

Speed Distribution of Vehicles

Daily speed distributions on several major suburban arterials were obtained from the city of Pleasanton, California. Three roads that had large traffic flows were chosen: Sunol Boulevard north of Mission Boulevard, which had 6,551 vehicles on March 25, 1996; Hopyard between Valley and Black, which had 8,301 vehicles on July 6, 1999; and Hopyard between Stoneridge and West Las Positas, which had 6,590 vehicles on June 21, 1999. These data were combined to obtain the speed distribution illustrated in Figure 1.

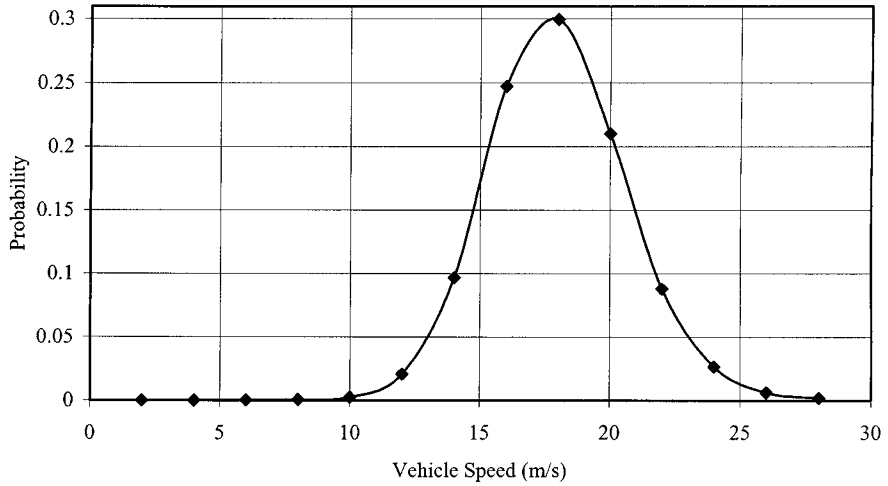

FIGURE 1 Speed distribution of approaching vehicles.

NOMINAL WARNING DESIGN

The nominal warning design was based on the trade-off among warning system effectiveness for both LDVs and trucks, frequency of nuisance alarms for LDVs, and severity of crashes. This design enabled the selection of the most appropriate warning distance for each approaching vehicle speed.

The crash scenario represented an LVNM with the rear crash-warning system at rest on a straight, dry, paved road, with a vehicle approaching in the same lane from the rear at speed V_o. The driver always detected the warning after the response time lag and applied emergency braking.

Stopping Distances of Approaching Vehicles

When a warning was issued, the stopping distance for the approaching vehicle was given by

$$R_d = -\frac{V_o^2}{2A_d} + (T_d + T_{sensor})V_o \tag{4}$$

where R_d is a distribution for each value of the approaching vehicle speed V_o. The distribution used for T_d is discussed above (see response Time Distribution: T_d). If the approaching vehicle was an LDV, then the distribution used for A_d was as discussed above (see Design Parameters for LDVs). If the approaching vehicle was a heavy vehicle, then the distribution used for A_d was as discussed above (see Design Parameters for Heavy Vehicles).

The corresponding *comfortable* stopping distance was given by

$$R_{comf} = -\frac{V_o^2}{2A_{comf}} + (T_d + T_{sensor} + T_{brake})V_o \tag{5}$$

where R_{comf} is a distribution for each value of the approaching vehicle speed V_o. The distribution used for A_{comf} was as discussed above. It is important to note that the values for comfortable braking did not include the delay time needed to initiate braking due to pressure buildup. Therefore, an additional 200-ms brake pressure delay time was included.

The difference between these two stopping distances (Equations 4 and 5) is crucial to the system design, because the warning must be issued at a distance longer than R_d to give the approaching driver time to avoid a crash. However, if issued at a distance greater than R_{comf}, the warning is likely to be seen as a nuisance alert.

Warning Design

Step 1

The first step was to compute the measures of effectiveness. The variables were defined as

R_w = distance of approaching vehicle from the stopped vehicle at which warning was issued (in meters),
P_{eff}(LDV) = probability that a warning was effective (i.e., resulted in no crash) when the approaching vehicle was an LDV,
P_{eff}(Trck) = probability that a warning was effective (i.e., resulted in no crash) when the approaching vehicle was a heavy vehicle,
P_{nuis} = probability that a warning was a nuisance for the approaching vehicle driver,
E_{sev}(LDV) = expected speed of stopped vehicle after a crash occurs if the crashing vehicle was an LDV (in meters per second), and
E_{sev}(Trck) = expected speed of stopped vehicle after a crash occurs if the crashing vehicle was a heavy vehicle (in meters per second).

The severity of a crash, when it occurred, was measured in terms of the change in speed of the stopped vehicle. It was done in two steps. Given a warning at a distance R_w and assuming that the driver responded to the warning by braking, the speed of the approaching vehicle at the time of impact was computed. Then, using the momentum transfer phenomenon that occurs immediately after a crash, the change in speed of the stopped vehicle was derived. This operation required the mass of different vehicle types in the computation. For each R_w value, the change in speed of the stopped vehicle due to the crash could be represented only as a distribution. Hence, the expected severity was computed based on that distribution.

All the probabilities were calculated directly from the probability distributions of the independent (input) variables, and no Monte Carlo simulations were used.

Step 2

For each speed of an approaching vehicle, an appropriate warning distance was selected based on trade-offs among the various measures of effectiveness by examining the plots of the quantities discussed above. In selecting warning distances, care was taken to maximize warning effectiveness for LDVs (i.e., the fraction of vehicle encounters for which the warning is issued early enough that the driver of an LDV has enough time to brake to avoid a crash) so that the number of LDV crashes was 0 or very small.

If this were the only criterion, one could select the warning distance to be as large as possible. This cannot be done because it is necessary to make trade-offs with other measures of effectiveness (MOEs) such as maximizing warning effectiveness for trucks (i.e., the fraction of vehicle encounters for which the warning is issued early enough that the driver of a truck has enough time to brake to avoid a crash) and minimizing nuisance warnings. One such plot is shown in Figure 2 for an approaching vehicle speed of 18 m/s. Clearly, a warning distance of 77 m is good when the approaching vehicle speed is 18 m/s, because the effectiveness of the warning was close to 100 percent when the approaching vehicle was an LDV or a truck, and the nuisance warnings were below 5 percent.

Step 3

The nominal warning design is shown in Figure 3. Measures of effectiveness as a function of the approaching vehicle speed with respect to the nominal design are shown in Figure 4. Notice that the effectiveness of the warning design is high with respect to both LDVs and trucks. For the small percentage of vehicles that crash, the expected severity is low, which reinforces the crash mitigation benefits of the warning design. The predicted number of nuisance alarms is low in the midspeed range. This range accommodates most of the vehicles on arterial roads. At a very low speed (i.e., 2 m/s) as well as at higher speeds (i.e., >24 m/s) the predicted number of nuisance alarms is higher, because

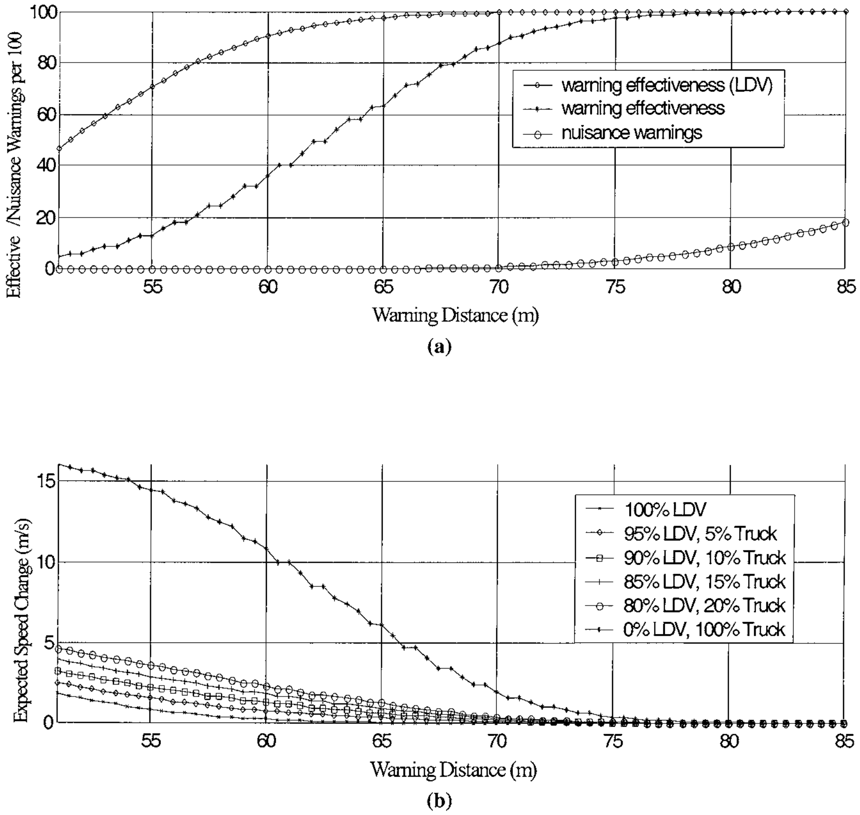

FIGURE 2 Warning distance versus effectiveness and nuisance alerts (*a*) and versus expected speed change (*b*) for approaching vehicle speed of 18 m/s (warning effectiveness (LDV) = fraction of vehicle encounters for which the warning is issued early enough that the driver of an LDV can brake to avoid a crash).

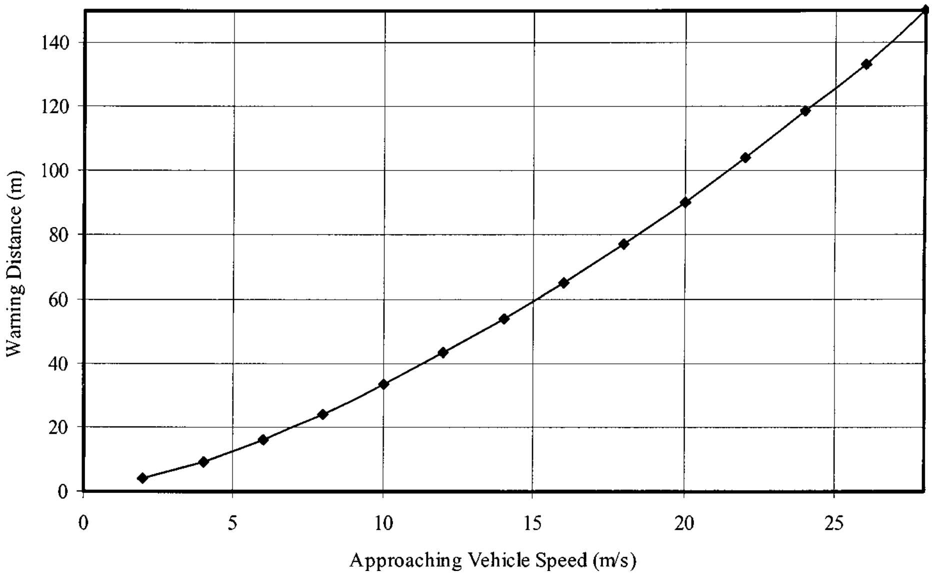

FIGURE 3 Nominal warning design.

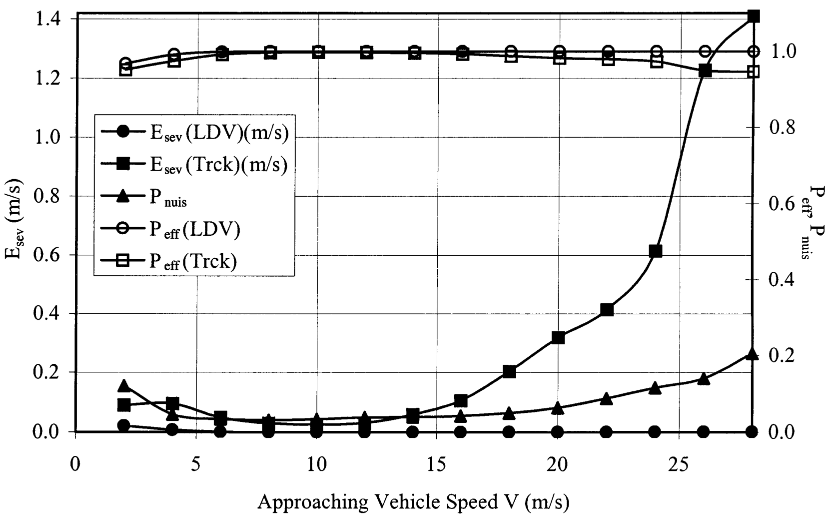

FIGURE 4 Measures of effectiveness with nominal warning design.

- Equation 3 gives conservative estimates for the 95th percentile values of comfortable braking and
- The CAMP authors acknowledged that their normal braking experiments should be viewed as aggressive normal braking, and in general, the values for normal braking deceleration would be lower than what they observed (*10*).

System designers may have different criteria from which they may determine unique warning design surfaces from the same data.

Expected Measures of Effectiveness Based on Speed Distribution

Having designed the warning system, it was possible to evaluate its effectiveness on arterial roads. The questions of interest were

1. What is the expected probability that the warning system is effective (i.e., results in no crash)?
2. What is the expected probability that the warning is a nuisance for drivers?
3. When a crash occurs, what is the expected severity of the crash (in meters per second)?

These quantities could be computed for various combinations of LDV and heavy vehicle percentages. The following variables were defined:

$E_{P_{\mathrm{nuis}}}$ = expected probability that the warning was a nuisance for the approaching driver on an arterial road,
$E_{P_{\mathrm{eff}}}(X_{\mathrm{LDV}}, Y_{\mathrm{Trck}})$ = expected probability that the warning was effective at avoiding a crash on an arterial road with X percent LDVs and Y percent trucks, and
$E_{E_{\mathrm{sev}}}(X_{\mathrm{LDV}}, Y_{\mathrm{Trck}})$ = expected speed of stopped vehicle after a crash on an arterial road with X percent LDVs and Y percent trucks (in meters per second).

The nominal warning design was used to compute the expected MOEs based on the speed distribution described earlier. The results are summarized in Table 2. The results indicate that the warning system is very effective in preventing crashes. The expected number of nuisance alarms is small, and for the very small percentage of vehicles that crash, the expected crash severity is negligible.

SENSITIVITY STUDIES

Table 3 describes the nominal case plus the 12 sensitivity studies. One additional warning design is given; the change in T_d required a new design to fully realize the benefits gained by faster response times.

Sensitivity to T_d

Sensitivity studies were conducted on the nominal warning design by using a different driver response time ($\mu = 0.82$ s, $\sigma = 0.18$ s) from Koppa et al. (*15*). The primary change here was that P_{nuis} increased and E_{sev}(Trck) decreased, particularly for the higher approach speeds. The other effectiveness measures improved slightly. The nominal warning design was clearly not optimal for this response time. Hence, a new warning design (Case 2) was developed for the new T_d

TABLE 2 Expected Measures of Effectiveness for Nominal Warning Design Based on Speed Distribution

		Truck Percentage				
		0%	5%	10%	15%	20%
Expected effectiveness of avoiding crashes (probability)	$E_{P_{\mathrm{eff}}}$	0.9997	0.999	0.9984	0.9978	0.997
Expected post-crash speed of stopped vehicle (m/s)	$E_{E_{\mathrm{sev}}}$	0.0002	0.0113	0.0225	0.0337	0.045
Expected nuisance (probability)	$E_{P_{\mathrm{nuis}}}$	0.0549				

TABLE 3 Sensitivity Studies

	Response Time (μ, σ) s	**A_{comf} (μ, σ) m/s^2**	**A_{d} (μ, σ) m/s^2**
Nominal	1.1, 0.305	Nominal	-5.5, 0.6
Sensitivity Cases			
Response Time (in T_{d})	0.82, 0.18 **(Case 1 and Case 2)**	Nominal	-5.5, 0.6
A_{comf}	1.1, 0.305	Nominal - 5% **Case 3**	-5.5, 0.6
A_{comf}	1.1, 0.305	Nominal - 10% **Case 4**	-5.5, 0.6
A_{comf}	1.1, 0.305	-2 **Case 5**	-5.5, 0.6
A_{d} Low	1.1, 0.305	Nominal	-4.5, 0.6 **(Case 6)**
A_{d} High	1.1, 0.305	Nominal	-6.5, 0.6 **(Case 7)**
Truck Mass Sensitivity	10% and 20% increase in truck masses **(Case 8 and Case 9)**		
Truck Population Sensitivity	1% Bobtails, 54% Straight Trucks, 45 % Truck Tractors. Empty/Loaded Truck ratio is 30% / 70% **(Case 10)**		
Sensor Sensitivity	With errors +1% in Range and -1% in Range Rate **(Case 11)**		
Sensor Sensitivity	With errors -1% in Range and +1% in Range Rate **(Case 12)**		

value. These results led to the conclusion that the design was sensitive to T_{d}. Thus, accurate values of T_{d} are essential to support the design of an effective system.

Sensitivity to A_{comf}

Three variations of mean A_{comf} values corresponding to Cases 3, 4, and 5 were used in sensitivity studies of the nominal design to mean A_{comf} value.

In the nominal case, values from Equation 3 were used to represent the mean value of the comfortable deceleration. The mean values of the comfortable deceleration were assumed to be 5 and 10 percent lower for Cases 3 and 4, respectively. In Case 5, the mean value of comfortable deceleration was chosen to be constant and independent of vehicle speed. The mean value of comfortable deceleration was fixed at –2 m/s^2, the midpoint of the spread of speed-dependent nominal values.

The only change was in P_{nuis}, which decreased at all speeds for Cases 3 and 4. The predicted number of nuisance alarms in the nominal design may be viewed as an upper bound. The results of Cases 3 and 4 reinforced the claim that slightly lower values for mean A_{comf} result in significant reduction in the predicted number of nuisance alarms based on the nominal design. For Case 5, P_{nuis} increased significantly at lower speeds and decreased to very low values at higher approach speeds. The other effectiveness measures showed no change. These results led to the conclusion that the prediction of number of nuisance alarms is quite sensitive to A_{comf}. Therefore, it is important to obtain accurate A_{comf} values to design a system that minimizes the frequency of nuisance alarms.

Sensitivity to A_{d}

Two variations of the mean A_{d} value were chosen for sensitivity studies of the nominal design to mean A_{d} value. In the nominal case, the mean A_{d} value chosen was –5.5 m/s^2. Sensitivity studies were carried out with the mean A_{d} values equal to –4.5 and –6.5 m/s^2 for Cases 6 and 7, respectively.

The only changes were in P_{eff}(LDV) and E_{sev}(LDV). P_{eff}(LDV) decreased slightly for Case 6 and increased slightly for Case 7. E_{sev}(LDV) increased slightly for Case 6 and decreased slightly for Case 7. These results led to the conclusion that the MOEs were less sensitive to the mean A_{d} value. For the sake of accuracy in future designs, it will be important to obtain lower bounds on the emergency braking decelerations for the normal population of LDV drivers.

Sensitivity to Truck Masses

Two variations of truck masses were chosen for sensitivity studies of the nominal design to truck masses. Sensitivity studies were carried out with increases in all truck masses of 10 and 20 percent for Cases 8 and 9, respectively. The only change was in E_{sev}(Trck). Results suggested that MOEs were only slightly sensitive to truck masses.

Sensitivity to Distribution of Truck Traffic

One variation of the truck population distribution was used in a sensitivity study of the nominal design, representing 1 percent bobtails, 54 percent straight trucks, and 45 percent truck-tractors, with an empty and loaded truck percentages of 30 and 70 percent, respectively (Case 10). The only changes were in P_{eff}(Trck) and E_{sev}(Trck). Results suggest that MOEs were only slightly sensitive to truck population distribution.

Sensitivity to Sensor Errors

It was assumed that the sensor had 1 percent errors in the range and range rate measurements. The two worst-case scenarios were considered, corresponding to +1 percent in range and –1 percent in range rate (Case 11) and −1 percent in range and +1 percent in range rate (Case 12).

For Case 11, all MOEs were affected. The frequency of nuisance alarms worsened while all the other MOEs improved. For Case 12, the frequency of nuisance alarms improved while all the other MOEs worsened. These findings imply that the design is quite sensitive to sensor errors. They suggest that it is critical to develop accurate models of sensor errors and to perform sensitivity studies on such models, to specify the needed sensor performance.

CONCLUSIONS

It is possible to design a rear-end warning system that can be effective in preventing crashes without generating excessive nuisance alerts. For the very small percentage of vehicles that would crash, the expected crash severity would be negligible. Values used for the nominal warning design parameters represented the best estimates based on an extensive literature search. Hence, the nominal warning design presented here can be forwarded as the best design case for subsequent experimental evaluation.

Based on the sensitivity studies conducted, the MOEs of the warning design clearly were sensitive to certain design parameters. Experimental research and field operational tests should be conducted to obtain accurate numerical values for the design parameters before a design is implemented on vehicles for widespread public use.

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