A FRONT-END ANALYSIS OF REAR-END CRASHES

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Abstract

This paper describes the application of a seven-step crash problem analysis methodology, as described in the preceding paper by Leasure (l), to rear-end crashes. The paper shows how modeling of rear-end crash scenarios and candidate countermeasure action has been used to analyze vehicle motion and driver actions, define and explain countermeasure action, predict effectiveness and benefits and, ultimately, guide future research. This process might be described as a "front-end" analysis of rear-end crashes and the prospects for preventing them through the application of advanced technology. The discussion focuses on lead-vehicle stationary crashes, the largest subclass of rear-end crashes. The principal countermeasure concept examined is a headway detection system that would detect "threatening" vehicles in a vehicle's forward travel path.

Introduction and Overview

The NHTSA Office of Crash Avoidance Research (OCAR), in conjunction with the Volpe National Transportation Systems Center (VNTSC), has initiated a multidisciplinary project designed to model target crash scenarios and Intelligent Vehicle Highway System (IVHS) technological interventions, to provide device effectiveness and benefits estimates, and to identify high-priority R&D needs relating to specific IVHS/crash avoidance countermeasure concepts. The project contractor is Battelle Memorial Institute (Contract No. DTRS-57-89-D-00086), with the major participation of subcontractors Arvin/Calspan, and Castle Rock Consultants. In the preceding paper, Leasure (1) described this program, its seven-step methodology, and its relationship to current and planned NHTSA research on IVHS safety-enhancing concepts.

The initial crash topics examined have been rear-end and road departure crashes, two crash types which each constitute about one-fourth of police-reported crashes. Each topic analysis has consisted of steps outlined in Figure 1. Borrowing jargon from the training profession, this process might be termed "front-end analysis*" of crash problems and prospective countermeasures. This paper addresses the results of our first "front-end analysis." Ironically, the topic is ***rear-end*** crashes!

This paper is based largely on the first major technical report of the Problem Definition/Analysis program, entitled ***Topical Report No.1 - Evaluation of IVHS Countermeasures for Collision Avoidance -- Rear End Cmshes,*** by Donald L. Hendricks et al (2). A technical report of the rear-end crash analysis is expected to be published by September, 1992. A companion report by Knipling and Yin (3) provided the statistics on crash problem size and statistical characteristics based on national databases.

Problem Definition/Analysis Methodology

1. *Quantify baseline crash problem size and describe crash characteristics.*
2. *Describe, analyze, and model target crash scenarios to permit understanding of principal crash causes and time and motion sequences.*
3. *Assess countermeasure concepts and technology to identify candidate solutions and describe functional operation.*
4. *Assess relevant "real world" factors, including human, environmental, and vehicle factors affecting countermeasure effectiveness.*
5. *Model countermeasure action to predict effectiveness and identify countermeasure functional requirements.*
6. *Derive benefits estimates based on the potential countermeasure effectiveness.*
7. *Identify priority technologica;, human factors, and other R&D issues.*

Figure 1

Methodology and Results

Rear-End Crash Problem Size and Characteristics

In 1990, there were approximately 1.5 million police-reported rear-end crashes on roadways with 2,078 associated fatalities. Rear-end crashes constituted about 23 percent of all police-reported crashes, but only about 5 percent of all fatalities. There were approximately 800,000 associated injuries, mostly of relatively mild severity (Sources: NHTSA General Estimates System and Fatal Accident Reporting System; see Reference 3).

* In systematic training development, a "front-end analysis" of job tasks, specific training needs, and optimal training methods and equipment is performed before work actually begins on the development of training materials or devices.

During its operational life (about 11.5 years on the average), a vehicle can be expected to he involved in 0.09 police-reported rear-end crashes as the striking vehicle, and another 0.09 as the struck vehicle. For each role (striking and struck), the expected number of involvements approximates the probability that a given vehicle will "need" a particular type of countermeasure during its operational life. In other words, there is a probability of approximately 0.09 that, during its operational life, a vehicle will "need" a countermeasure against striking another vehicle in a (police-reported) rear-end crash. The same approximate probability (0.09) applies to the struck vehicle role.

The above statistics relate to all vehicle types combined. Table 1 disaggregates and compares involvements as the stiking unit of two vehicle types of particular interest, passenger vehicles (here defined as cars, light trucks, and vans) and combination-unit trucks. Only about 2 percent of all rear-end crashes involve a combination-unit truck as the striking unit, and combination-unit trucks have a much lower rate of involvement per vehicle mile traveled (VMT) than do passenger vehicles. These statistics imply that combination-unit trucks (as striking vehicles) are not a large part of the rear-end crash problem, particularly in terms of absolute number of crashes.

TABLE 1: COMPARISON OF STATISTICS ON PASSENGER VEHICLES AND COMBINATION-UNIT TRUCK INVOLVEMENTS IN POLICE-REPORTED REAR-EM) CRASHES AS *THE STRIKING UNIT. Source: (3)*

Statistic / Vehicle Type:	PVs	CU Trks
Annual Crashes (1990 GES)	**1,436,000**	**33,000**
Rate of Involvement Per 100 M Veh. Miles Traveled (V-MT)	**72**	**34**
Expected Number of Involvements Over Vehicle Life	**0.09**	**0.24**
Fatalities Per Police-Reported Crash (1990 FARS and 1990 GES	**0.001**	**0.01**

However, due to their greater exposure (average miles traveled), combination-unit trucks have a much higher expected number of involvements in target crashes during their operational lives than do passenger vehicles; i.e., an average of 0.24 involvements as the striking vehicle in police-reported rear-end crashes versus 0.09 for passenger vehicles (see Table 1). In regard to vehicle-based countermeasure concepts, these *likelihood* statistics (i.e., statistics on expected numbers of involvements) are much more relevant to potential payoffs than are statistics on ***rates*** of involvement. Indeed, for manufacturer-installed devices lasting the life of the vehicle, rates of involvement per mile traveled are irrelevant, whereas likelihood statistics are critical in determining potential payoffs.

In addition, rear-end crashes involving combination-unit trucks as the striking unit are approximately ten times more likely to result in a fatality than are those involving passenger vehicles as the striking unit (see Table 1). The greater likelihood of combination-unit trucks to be involved in target crashes, combined with the far greater average severity of their crashes, makes combination-unit trucks an attractive population for early cost-beneficial installation of countermeasures to rear-end crashes (as well as many other crash types).

A method was developed to estimate the number of ***non-poke-reported*** crashes based on the proportion of police-reported rear-end crashes that were property damage only (the lowest police-reported severity category) and the estimated total number of non-police-reported crashes of all types from Miller, 1991 (4). Miller estimates that there are about 7.8 million non-police-reported crashes annually. The basic assumption of the current estimate of non-poke-reported target crashes was that non-police-reported crashes are distributed by crash type and characteristics in the same proportions as police-reported property-damage-only (PDO) crashes. GES statistics for 1990 showed that there were a total of 4.4 million police-reported PDO crashes, about 1.0 million (23 percent) were rear-end crashes. Based on this proportion, it was estimated that there are about 1.75 million non-police-reported rear-end crashes annually (3).

The accuracy of this estimate of 1.75 million non-poke-reported rear-end crashes is dependent both on the accuracy of Miller' s estimate of all non-police-reported crashes (7.8 million) and the assumption of crash type proportionality between non-police-reported crashes and police-reported PDO crashes. A 1981 report by Greenblatt et al (5) estimated that there are 0.89 non-police-reported crashes for each police-reported crash, yielding a somewhat smaller estimate for all non-police-reported crashes (e.g., 5.8 million for 1990). Also, the assumption of proportionality may be questionable due to the fact that rear-end crashes always involve at least two vehicles, and that the driver of the striking vehicle is almost always legally culpable. Thus, a higher proportion of rear-end crashes may be reported to the police than other crash types involving single vehicles or indeterminate culpability. If either or both of these caveats are correct, then the estimate of 1.75 million non-police-reported rear-end crashes would be somewhat high.

An algorithm for estimating traffic delay caused by crashes, based on their location (with urban and divided highway crashes causing the greatest delay), indicated that rear-end crashes cause roughly one-third of all crash-caused delay. It seems reasonable that rear-end crashes would cause a disproportionate amount of delay compared to other crash types, given that rear-end crashes often occur on urban roadways, in particular on freeways, during periods of high traffic density.Moreover, rear-end crashes often involve two (or more) vehicles that must be towed from the roadway before traffic flow can return to normal.

The most important classification within the rear-end crash category is lead vehicle stationary (RE-LVS) vs. lead-vehicle moving (RE-LVM). Comparison of the RR-LVS and RR-LVM statistics (Table 2) shows that there are more than twice as many RE-LVS crashes (e.g., 1.05 million police-reported crashes during 1990) as RR-LVM crashes (0.46 million PR crashes). RELVM crashes are, on the average, somewhat more severe; for example, they are almost twice as likely to result in a fatality. But RR-LVS crashes constitute the larger overall problem in terms of crashes, injuries, and fatalities.

TABLE 2: CRASH PROBLEM SIZE STATISTICS FOR REAR-END, LEAD-VEHICLE STATIONARY (RE-LVS) AND REAR-END, LEAD-VEHlCLE MOVING (RE-LVM) CRASHES*. Source: 1990 GES, reported in (3)

Crash Subtype: Statistic and Source	Rear-End, Lead Vehicle stationary (RE-LVS)	Rear-End, Lead Vehicle Moving (RE-LVM)
Annual Police-Reported (PR) Crashes	**1.05 Million**	**0.46 Million**
Annual Non-Fatal Injuries in PR Crashes	**570,000**	**240,000**
Percent of All PR Crashes	**16.2%**	**7.1%**
Annual Fatalities**	**1,600**	**1,300**
Fatalities Per PR Crash**	**0.0016**	**0.0030**

* **Rear-end crash LVS vs. LVM unknowns (about 11 percent of the total) have been distributed proportionately across subtypes so that the LVS + LVM total equals all rear-end crashes.**

* **GES fatality statistics are used in this table because the Fatal Accident Reporting System (PARS) does not differentiate RE-LVS from RE-LVM crashes. The FARS count for all rear-end crash fatalitiw in 1990 was 2,078. Imputing the GES RE-LVS vs. RE-LVM proportion to the FARS total rear-end crash fatality count yields estimates of 1,146 RE-LVS fatalities and 932 RE-LVM fatalities for 1990. The associated fatalities/PR crash proportions for RE-LVS and RE-LVM crashes are 0.0011 and 0.0020, respectively.**

The statistical characteristics of rear-end crashes as evident in the General Estimates System (GES) do not reveal widespread distinctive patterns of occurrence such as roadway or environmental factors. Most crashes (both RE-LVS and RE-LVM) occur during daylight hours on dry, straight roadways. The most common coded pre-crash vehicle maneuver for the striking vehicle is simply “going straight” (84 percent overall). For RE-LVM crashes, about half of the struck vehicles are “going straight” and about one-fourth are “slowing or stopping.” Obstruction of driver vision is rarely noted.

A few notable differences in the conditions of occurrence of RE-LVS and RE-LVM crashes include the fact that most RE-LVM crashes (54 percent) are non-junction crashes (i.e., not intersection or intersection-related), whereas only 35 percent of RE-LVS crashes are non-junction. In addition, RE-LVM crashes are somewhat more likely to occur on divided highways and other higher-speed roadways than are RE-LVS crashes.

Indiana Tre-Level study (6) findings (see Figure 2) on the causal factors associated with 45 RE-LVS and 12 RE-LVM crashes (of the 420 total cases in the Tri-Level in-depth sample) were accessed. The analysis of the Tri-Level cases by crash type was possible through the use of an enhanced Tri-Level study data file developed by NHTSA (7). The Tri-Level statistics portray rear-end crashes as resulting largely from driver inattention and other forms of delayed recognition, with little involvement of vehicle factors, indirect human causes (e.g., alcohol), or environmental factors. This pattern is true for both RE-LVS and RE-LVM crash subtypes -- especially the RE-LVS crashes.

Rear-End Crash Causal Factors

Principal causal factors identified in Indiana Tri-Level Study (6). Indentation reflects Tri-Level taxonomy of crash causes.

<u>Rear-End Lead Vehicle Stationary (RE-LVS: 45 cases total)</u>:

- Vehicular factors (11%)
- Human causes (93 %)
  - Direct human causes (93%)
    - Recognition errors (82 %)
      - Recognition delays – reasons identified (69 %)
        - Inattention (42 %)
          - Traffic stopped or slowing (33%)
          - Event in car (e.g., sudden noise) (13 %)
        - Internal distraction (4%)
        - External distraction (11%)
    - Decision errors (24 %)
  - Indirect human causes (e.g., alcohol, drugs (9%)
- Environmental causes (e.g., slick roads, view obstructions) (9 %)

<u>Rear-End, Lead Vehicle Moving (RE-LVM: 12 cases total)</u>:

- Vehicular factors (17%)
  - Brake system (17%)
- Human causes (92%)
  - Direct human causes (92%)
    - Recognition errors (67%)
      - Recognition delays – reasons identified (67%)
        - Inattention (25%)
          - Traffic stopped or slowing (25%)
          - Event in car (e.g., sudden noise) (17%)
        - External diction (33 %)
    - Decision errors (50%)
      - False assumption (e.g., assumed car was turning did not) (42%)
- Environmental causes (e.g., slick roads, view obstruct.) (17%).

Figure 2

<u>Analysis of Crash Scenarios</u>

Seventy-four (74) rear-end cases from the 1991 National Accident Sampling System (NASS) Crashworthiness Data System (CDS) files were randomly selected for intensive clinical analysis. A principal causal factor was identified for each crash based on an assessment of all information in each case file (e.g., Police Accident Report, driver statements, scene and vehicle photos). Table 3 (next page) shows that driver inattention (including various forms of distraction) is the predominant causal factor in rear-end crashes, particularly RE-LVS crashes.

In addition to the determination of causal factors, an effort was made to reconstruct each collision scenario.Based on the information in the case file (e.g., scene diagrams, photos, narratives, vehicle damage), parameters such as the following were estimated: vehicle travel speed (lead and following vehicles), brake inputs, closing speeds, coefficients of friction, impact speeds, impact delta Vs [i.e., velocity change during the impact, a measure of collision severity). In 24 of the cases (18 RE-LVS and 6 RE-LVM), there were sufficient data to permit the reconstruction of these accident parameters. (Note: the NASS CDS was designed to provide crashworthiness data, not collision scenario data; thus the relatively low number of cases with information available to support the collision scenario analysis).

TABLE 3: PRINCIPAL CAUSAL FACTORS IDENTIFIED FOR 74 REAR-END CRASHES IN THE CLINICAL SAMPLE (1991 NASS CASES)

Crash Subtype: Principal Causal Factor	Rear-End, Lead Vehicle Stationary	Rear-End, Lead Vehicle Moving
Driver Inattentive	**39**	**9**
Driver Inattentive and Following Too Closely	**6**	**2**
Following Too Closely	**5**	**1**
Alcohol Involvement (Regardless of Immediate Driver Error)	**5**	**1**
Miscellaneous other	**2**	**4**
Total Cases	**57**	**17**

The remainder of this discussion will focus on RE-LVS crashes, with occasional comparisons to the RE-LVM subtype. The crash data presented above have documented the large baseline problem size of the RE-LVS subtype. Countermeasure modeling (addressed below) seems to show that the RE-LVS subtype is potentially amenable to effective prevention through the application of IVHS technology.

Table 4 presents the results of the reconstruction of the 18 RE-LVS cases for two key collision parameters, pre-crash travel speed and impact speed. The . impact speed values were available from the NASS CDS case crashworthiness reconstructions. The estimated pre-crash travel speeds were derived based on impact speeds, braking distances, coeffkients of friction, and other pertinent data.

TABLE 4: COLLISION PARAMETERS OF 18 RECONSTRUCTED RE-LVS CASES

Case #	Pre-Crash Travel Speed **(MPH)**	Impact Speed **(MPH)**
1	24.6	24.6
2	26.4	26.4
3	26.6	26.6
4	27.2	24.9
5	30.7	26.6
6	31.0	19.5
7	31.9	31.9
8	32.6	32.6
9	34.3	34.3
10	35.2	29.8
11	35.8	35.8
12	37.4	23.2
13	38.8	29.2
14	39.7	22.5
15	39.8	22.2
16	41.2	41.2
17	48.7	36.3
18	57.1	30.7

The 18 cases shown in Table 4 are known to be a non-representative sample of all RE-LVS crashes. The NASS CDS oversamples more severe crashes relative to their actual proportions in the crash population. Thus there is a known bias in the sample toward more severe crashes. In RE-LVS crash countermeasure effectiveness modeling (both here and in the full technical report), this bias is addressed through the use of differential case weighting by crash severity. In addition to the known bias toward more severe crashes, there is a possible but unknown bias due to the fact that some cases could be reconstructed based on available data, whereas others could not.

Assessment of Potential IVHS Technologies

Driver inattention (including distraction) and/or following too closely was cited as the principal causal factor in 50 of 57 of the clinical sample RELVS crashes (Table 3). Recall also the already-cited Indiana Tri-Level study findings on RE-LVS crashes indicated major roles for inattention/distraction as causal factors. Accordingly, the functional countermeasure concept of ***headway detection*** (HD) was identified as being most applicable to RELVS crashes. An HD system would measure the distance as well as the relative speed between the subject vehicle and vehicles ahead. A safe headway margin could be defined as the distance the driver needs in front of his or her vehicle to react safely to changes in traffic flow and to come to a complete stop without making contact with the vehicle ahead.

The HD system could also detect non-vehicle obstacles in the travel lane ahead. However, this function is more problematic due to a need for additional signal processing to identify true crash threats (i.e., identify "friend or foe") and minimize false alarms.

In the analysis the HD system was viewed primarily as a potential warning system, although an alternative system response to detection of a threat would be to immediately provide some measure of vehicle control; e.g., immediate soft braking. This article addresses only the warning system approach. Also, it is assumed that braking rather than steering is likely to be the most probable, and safest, driver response to same lane, forward-field crash threats due to the hazards of "panic" lane changes or crossing over into the oncoming traffic lane.

Review of available technologies and their capabilities indicated that an active laser radar or a microwave radar system (perhaps more accurately described as a millimeter wave system) would be the most likely candidates to satisfy the functional requirements of the HD system. A number of such systems already exist in both prototype and commercially-available configurations. Both the active laser radar and microwave radar systems employ a transmitter on the following vehicle which emits electromagnetic energy in the direction of the lead vehicle. A portion of this energy is reflected from the lead vehicle and intercepted by a receiver on the following vehicle. Detection of targets and determination of their distance and closing speeds are accomplished using measurements of elapsed time between emission and reception of the signal. The computational power needed for signal processing and analysis for such a system is expected to be small compared to the computer capabilities expected in vehicles in just a few years.

To reduce false alarms to manageable levels, an optimal system would likely involve lead vehicles equipped with some form of reflector, and, ideally, would employ some form of lane encoding of the lead vehicle. In other words, the system would be able to discriminate vehicles from objects and vehicles in the forward travel lane from vehicles just outside the travel lane (e.g., vehicles in adjacent lanes). Other logic routines would be added to the system to reduce false alarms; for example, the system would likely be programmed to not sound an alarm if the driver's foot were on the brake or, alternatively, if some minimum threshold level of braking force were being applied.

"Strawman" Functional Characteristics

Due to the preliminary "front-end" nature of the analysis, detailed trade-off studies or development of comprehensive performance requirements were not performed. Existing systems were not evaluated and detailed future system parameters were not recommended. However, some key functional characteristics of the conceptualized HD countermeasure may be hypothesized based on existing technology and the highway operating environment of the system. Based on the characteristics of existing systems, the maximum operating range might be on the order of 300 feet (although other ranges are possible and several alternatives were modeled). The total "system delay" (i.e., the time from the detection of the obstacle to initiation of the warning) would be approximately 0.25 seconds Driver reaction time (RT) to the warning is variable and is considered as part of the modeling of countermeasure action. Following the initiation of braking, there would be an average delay of 0.50 seconds until maximum braking is reached. After maximum braking is reached, the actual braking deceleration magnitude may vary among vehicles and roadway types and surface conditions. Thus, this variable is considered as part of the modeling.

The "strawman" maximum operating range suggested here is 300 feet, although it is clear that a *fixed* operational range of 300 feet would be too simplistic and would lead to false alarm problems. At low to moderate speeds, an HD system that always operated at a functional range of 300 feet would likely inundate the driver with false alarms. For example, a driver/vehicle* traveling in traffic at 30 mph (44 feet/second) requires only about 100 to 150 feet to brake to a stop following detection of stopped vehicle or other obstacle in its forward path (this distance includes distance traveled during the driver RT plus the distance traveled after braking). At 30 mph, an object 300 feet ahead would normally constitute no threat and therefore should not evoke an alarm.

Accordingly, the HD system would need to be designed to ***reduce*** its functional range (i.e., the critical separation at which it would begin to monitor and, if warranted, sound an alarm) dynamically when the vehicle is traveling at lower speeds. A reasonable approach to formulating a specific algorithm or function for this functional range reduction would be to base it primarily on driver/vehicles' abilities to react and brake to avoid impending crashes. Equation (1) below shows the critical monitoring distance needed by an HD system and driver/vehicles to avoid a crash. This equation incorporates the basic kinematic relationship between the following and lead vehicles, as well as requirements for HD system response and driver reaction.

$$D_{HD} = T_D V_o - 0.13V_o + V_o^2/2A \qquad (1)$$

Where: D_{HD} = Total distance (in feet) needed by the **HD** system for system response, driver reaction, and braking.

T_D = Time response delay of driver/vehicle system; includes HD system detection delay, driver RT, and delay to maximum braking.

V_o = Initial velocity of following vehicle (in feet/second).

A = Rate of braking deceleration after maximum braking is reached; expressed in feet/second^2.

The expression $0.13V_o$ in Equation (1) is a correction factor to account for the fact that a degree of braking does occur between the onset of braking and maximum braking efficiency.

The hypothetical system would be programmed to "know" the vehicle's travel speed, but would not "know" the expected time response delay (specifically, the driver RT component) or the expected rate of deceleration. (Actually, more advanced systems may be "smart" in regard to these parameters, but this capability is beyond the scope of this initial countermeasure concept.) Thus, the two major variables affecting the definition of the monitoring algorithm are T_D and A. A range of system operating parameters could be defined, based on the nominal values selected for these two variables.

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* The phrase "driver/vehicle" is used here to refer to the total "system performance" of the driver and vehicle; e.g., both driver RT and condition of brakes (as well as roadway factors) determine how quickly a vehicle can brake to a stop following the appearance of a crash threat.

Figure 3 presents three hypothetical HD system range functions which all dynamically reduce system operational range at lower vehicle speeds. All three are based on the same hypothetical *distributions* of driver RT and vehicle emergency braking deceleration, but each is based on a different set of assumptions about specific driver RT and braking deceleration values.

The distributions of driver RT and vehicle braking used as the basis for Figure 3 are intended to be realistic but simplified approximations of actual driver/vehicle performance which might be expected. Driver braking RT is assumed to be a standard normal distribution with a mean of 1.10 seconds and a standard deviation (SD) of 0.25 seconds. These RT Mean and SD values are consistent with Olson et al (8), although the standard normal distribution is hypothesized here for convenience (the actual driver RT distribution is probably somewhat positively skewed). The emergency vehicle braking distribution is assumed to have a mean of 0.60g (19.32 feet/second^2) and an SD of 0.12g (3.86 feet/second^2). Again, the normal distribution is hypothesized for convenience; for braking the actual distribution is likely to be somewhat negatively skewed since braking is frequently degraded by slippery road conditions or other factors.

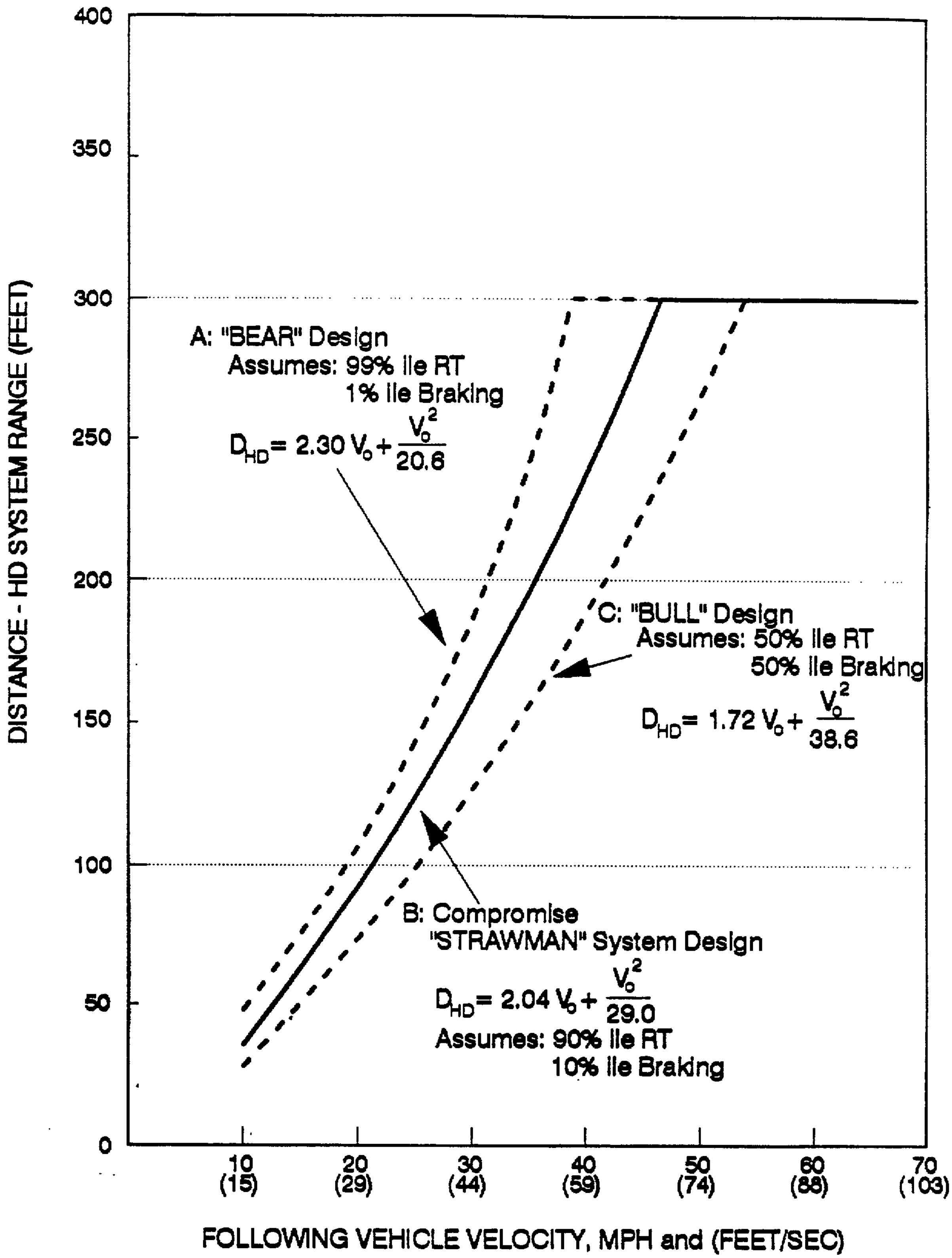
The three curves in Figure 3 illustrate the trade-off that exists between the need to provide sufficient time for driver/vehicles to react and brake, and the need to minimize false alarms. We've borrowed some jargon from the stock market to describe these curves. Curve "A" is a "bear" design that accommodates the very slowest-reacting drivers with the slowest emergency braking decelerations (e.g., poor brakes or wet pavement). Specifically, Curve "A" sets its parameters based on the assumption of the 99th percentile driver (RT = 1.68 seconds) and 1st percentile emergency braking (A = 10.3 feet/second^2). Theoretically, a device with the operating characteristics of Curve "A" would prevent virtually ***all applicable*** crashes. Given these long operating ranges, virtually all driver/vehicles would be able to react and brake in sufficient time to avoid the RE-LVS crash. On the other hand, this system would undoubtedly generate many false alarms for most driver/vehicles.

At the other extreme, Curve "C" represents a "bull" approach based on the assumption of a 50th percentile driver (RT = 1.10 seconds) and vehicle braking (A = 19.32 feet/second^2). The Curve "C" system operating range would provide ***average*** driver/vehicles just enough time to avoid the crash threat. All driver/vehicles with below average performance (based on driver RT and braking deceleration) would not avoid the impact (although some severity reduction might be provided).

Curve "B" represents a compromise design which assumes 90th percentile driver RT (RT = 1.42 seconds) and 10th percentile braking (A = 14.5 feet/second^2). As in Curve "A", the vast majority of driver/vehicles would be capable of performing within these parameters to avoid crashes. However, the percentage is not as high as in Curve "A". Curve "B" would be expected to generate fewer false alarms than Curve "A," but more than Curve "C."

For the purposes of the countermeasure modeling presented in this report, Curve "B" is proposed as a compromise "strawman" system design. Future research would evaluate this design and iterations of it, with specific focus on the effectiveness vs. false alarm tradeoff.

Figure 3: Alternative HD System Models For RE-LVS Crashes



Relevant Human, Environmental. and Vehicle Factors

A number of complicating factors -- human, environmental, and vehicle -- were identified. These are "real world" constraints and problems that would need to be overcome or accommodated in order for an HD system to be viable. The research literature relating to these factors was reviewed to assess their likely relevance and impact on driver/vehicle performance.

Driver human factors considerations include driver braking RT, effect of false alarms, compensatory risktaking, driver non-acceptance of the system, and unsafe driving behavior. The section above presented a hypothetical driver RT for braking. Modeling predictions of driver/vehicle performance using an HD warning system are dependent on the actual driver RT distribution in the context of the actual deployed HD system. Future test and evaluation of prototype HD systems will assess driver RT and other driver performance parameters relevant to system effectiveness.

The false alarm issue was judged to be more problematic -- a tradeoff exists between detection range (and thus probability of headway detection with sufficient time for a successful driver response) and frequency of false alarms. This issue will need to be addressed experimentally in the context of specific functional system configurations as part of future countermeasure R&D. Other false alarm-related issues apart from the functional range question include range accuracy, sensory threshold, and target size/shape criteria.

Compensatory risktaking, driver non-acceptance of the system, and unsafe driving behavior (including driving while intoxicated) are likely to compromise the actual effectiveness of any HD system (and other crash avoidance countermeasures). Compensatory risktaking refers to the (as yet unquantified and unexplicated) tendency of drivers to increase their level of risktaking "in response to" improvements in safety margins; e.g., to follow more closely or drive less attentively if an HD system is available to assist them. Driver non-acceptance (e.g., disabling of the system) and unsafe driving behavior (e.g., making an unsafe driving maneuver regardless of risks or warnings) are likely to degrade overall countermeasure effectiveness; for these drivers the system is essentially non-operative.

Practical vehicle considerations include effects of road dirt and poor maintenance, and effects of future changes in braking efficiency (e.g., because of future widespread use of antilock braking systems) on the effectiveness of the HD system.

Environmental considerations include potential health risks posed by the radar system (judged to be minimal for millimeter radar sensing systems) and degrading effects of heavy precipitation on system performance. Probably the most vexing problem is that of roadway configuration over the forward scanning field. Since these systems are line-of-sight, roadway curves, hillcrests, dips, and obscuring features may all affect the actual system range and performance. Irregularities in the roadway surface may also disrupt forward scanning. Roadway configuration considerations underscore the need for "lane locking" capabilities for the scanning beam and/or lane-encoding features in lead vehicle reflectors so that in-lane vehicles can be discriminated from vehicles and objects outside of the lane of travel.

Models of Countermeasure Action

The major purpose of modeling countermeasure action is to assess potential ***theoretical*** system effectiveness. Normally, such models are based on a set of mathematical formulas, simplifying assumptions regarding values in the formulas, and a limited number of empirical data points. These models are intended to be realistic (e.g., they use representative values for driver reaction time and vehicle panic braking), and to provide a perspective on potential system effectiveness. However, the models should ***not be interpreted as predictions of the actual affectiveness of deployed system.*** Unlike theoretical models, actual deployed systems are subject to an array of human, vehicle, and environmental "real world factors" that will generally have the effect of degrading system effectiveness below those levels predicted by theory. The countermeasure modeling performed under this program is intended to be a heuristic process, not an attempt to definitely capture, quantify, and sum all the factors that would affect system performance.

For the RE-LVS crash type, the principal modeling parameters are following vehicle velocity, distance/gap between vehicles, driver/vehicle response delay (HD system detection delay + driver RT + delay to maximum braking), and braking efficiency (after maximum braking is reached). Figure 3 presented three hypothetical system models for an HD system responding to stationary crash threats. Curve "B" in Figure 3 is employed here as the assumed system design for modeling theoretical system effectiveness. In Curve "B", the maximum HD system operating range is assumed to be 300 feet. Driver RT is assumed to be 1.42 seconds (the 90th percentile RT per the distribution hypothesized). When assumed time delays for initial system response (0.25 seconds), driver RT, and initial-to-full braking application (0.50 seconds) are all included, the total benchmark time delay is 2.17 seconds (0.25 + 1.42 + 0.50= 2.17). Maximum braking is assumed to be 0.45g or 14.5 feet/second* (10th percentile braking per the distribution hypothesized). Substituting these values for time delay and braking level into Equation (1) provides the following critical separation distance curve for distances up to 300 feet:

$$D_{HD} = 2.04V_o + V_o^2/29.0 \qquad (2)$$

Where: D_{HD} = Distance (in feet) provided by HD system for braking.

T_D = Time response delay of driver/vehicle system (HD system detection delay + driver RT + delay to maximum braking; here assumed to be 0.25 + 1.42 + 0.50 = 2.17 seconds).

V_o = Initial velocity of following vehicle (in feet/second).

An additional assumption implicit in the equation is that the lead vehicle is stationary for the entire period of time it is within the detection range of the HD system. This is a more conservative assumption than the alternative assumption that the lead vehicle was braking and came to a stop just prior to impact since, in the latter case, more stopping distance would be available for the following vehicle.

Assuming constant HD system performance levels (i.e., a constant 0.25 second system delay), the *actual* distance needed by driver/vehicles is totally dependent on the performance characteristics of the driver and the vehicle. Figure 4 illustrates five hypothetical combinations of driver and vehicle performance levels in relation to our "strawman" system design. Curve "F" models the "average" driver/vehicle -- i.e., average driver RT and average braking. At all system ranges (and associated vehicle velocities) up to 300 feet, there is sufficient time/distance for the HD system, driver, and vehicle to react and brake to a stop. At 30 mph, the "strawman" HD system provides a "safety margin" of about 30 feet; that is, the driver/vehicle would brake to a stop about 30 feet short of the lead vehicle. In the figure, this is the vertical distance between the design curve and Curve "F" at the 30 mph pre-crash velocity.

Curves "E" and "G" represent relatively "slow-reacting" and "fast-reacting" driver/vehicles, respectively. Curve "E" represents a driver with an RT that is 1 standard deviation above the mean (also equal to the 84th percentile RT) who is driving a vehicle that decelerates at 1 standard deviation below the mean (the 16th percentile). This relatively slow-reacting driver/vehicle still avoids the crash at all velocities up to about 48 mph, where the 300 foot HD system limit is reached. The vast majority of driver/vehicles would fall between Curves "E" and "G," since they would generally have to deviate significantly from the mean on both dimensions to fall outside these bounds.

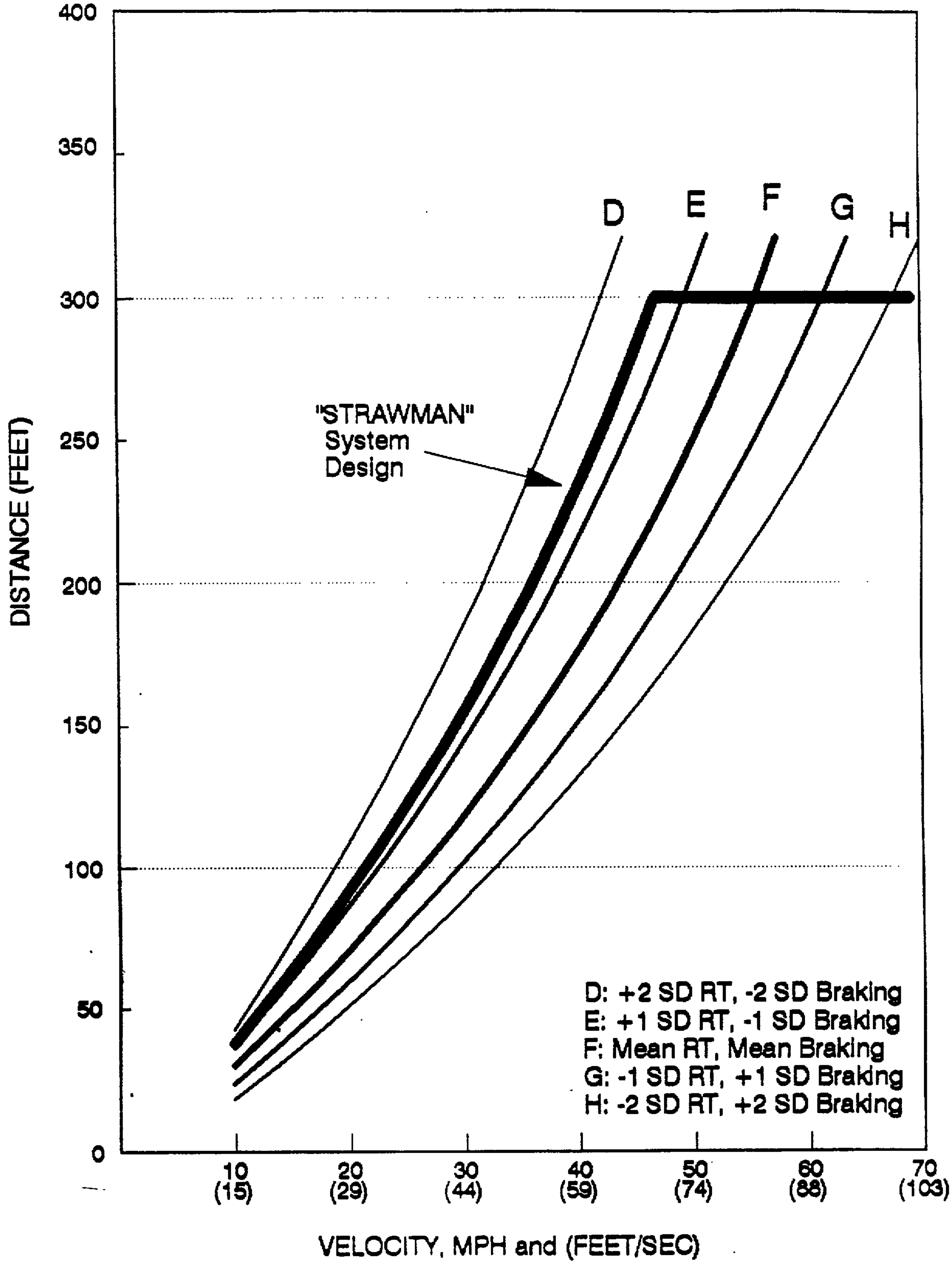
Curve "D" represents an extremely slow-reacting driver/vehicle -- very long RT (93th percentile) and very slow braking deceleration (2nd percentile). These driver/vehicles would not avoid the collision at any pre-crash speed, although some reduction of collision severity would occur.

Curve "H" is a "super-fast-reacting" driver/vehicle. The strawman HD system would provide a wide margin of safety for these driver/vehicles; e.g., nearly 70 feet at a 30 mph pre-crash speed. For these driver/vehicles, the system provides crash avoidance at pre-crash speeds up to nearly 70 mph, but would generate many false alarms.

A review of Table 4 reveals that 17 of the 18 reconstructed clinical sample cases had estimated pre-crash speeds equal to or less than 48.7 mph, and would be prevented by the HD system for the average driver/vehicle (i.e., Curve "F" in Figure 4). However, the range of driver/vehicle performance characteristics shown in Figure 4 illustrates that the 17 crashes avoided by the *average* driver/vehicle would not be avoided by ***all*** driver/vehicles, and that the 18th case, not avoided by the average driver/vehicle, nevertheless could be avoided by some driver/vehicles.

To better quantify these modeling results for a full and realistic range of driver and vehicle capabilities, a simplified Monte Carlo simulation was performed. One hundred different driver RT and vehicle braking combinations (selected from the hypothetical distributions already presented) were modeled for each case in relation to the "strawman" HD system design. The 100 combinations represented 10 different driver RTs (5th percentile, 15th percentile, 25th percentile, etc.), each paired with 10 different braking decelerations. Furthermore, each case was weighted by crash severity to compensate for the sample bias toward more severe crashes. This simplified Monte Carlo simulation indicated that

Figure 4: Variations in Driver Performance (RT) and Vehicle Performance (Braking) in Relation to HD System Design



approximately 92 percent of applicable RE-LVS crashes would be prevented by the modeled system.

Obviously, these are "ideal world" results. They assume no degradation of effectiveness due to any of the "real world" factors described above; for example, they assume that all roadways are straight and level enough for the HD scan to lock onto the roadway ahead and detect crash threats in the vehicle's travel lane. The range of braking efficiencies modeled does not include roads that are extremely slippery due to ice or snow, and thus where normal braking could not occur. Curved, hilly, and/or icy roads are examples of "real world" factors that would attenuate actual system performance below "theoretical" levels such as this 92 percent effectiveness estimate for target RE-LVS crashes. For example, in the 1990 GES, 69 percent of RE-LVS crashes occurred on roadways that were not coded as curved, hilly, or icy or snow-covered. If this 69 percent statistic represents the percentage of crash sites in which the HD system would actually function as conceived, then the adjusted system effectiveness based on the clinical sample results would be (.92)(.69) = .64. The actual magnitudes of significant system performance-degrading factors are to be determined in future research. Research may show the attenuating effects of these "real world" factors on countermeasure effectiveness to be quite significant.

Benefits

The countermeasure modeling presented in this report indicates that the potential exists for prevention of a significant portion of the 1.05 million annual police-reported RE-LVS crashes through the application of HD system technology. When hypothesized HD system countermeasure functional parameters were applied to the clinical sample cases assuming a range of driver and vehicle performance capabilities, 92 percent were found to be theoretically-preventable through the application of the HD countermeasure system.

Prevention of police-reported RE-LVS crashes is just one category of prospective benefits. In addition, there would be several other important categories of crash reduction:

* Prevention of some portion of the 0.46 million annual RE-LVM crashes (modeling not addressed in this paper)

* Prevention of many of the roughly 1.75 million annual non-police-reported rear-end crashes,- Countermeasure effectiveness for these crashes may even be ***greater than*** for police-reported crashes due to their generally lower severities and associated closing speeds. .

* Severity reduction of applicable rear-end crashes (RE-LVS and RE-LVM, police-reported and non-police-reported) that are not prevented by the system.

* Reductions in rear-end crash-caused delay generally proportionate to the reduction in crashes.

Although the "modeled" effectiveness of the 300-foot HD system for the 18 sample cases was 92 percent prevention, this level of effectiveness (and proportionate benefits) could not be achieved in the "real world." ***Attenuating factors*** such as the following would reduce the actual effectiveness of the system:

* The HD system primarily addresses rear-end crashes that are inattention-related and/or following-too-closely related. Other causal factors (e.g., unsafe driving acts, false assumption about other vehicle's path of travel, vehicle component failure, sudden physiological impairment of driver) would not be addressed as effectively.

* As noted earlier, the HD system might be assumed to operate effectively only on roadways that are reasonably smooth, straight, and level. The vehicle's braking system will operate normally only on non-slippery roadways.

* Drivers might "compensate" for the increased margin of safety provided to them by the HD system by following other vehicles more closely and/or becoming less attentive to obstacles in their forward field.

* Excessive false alarms associated with the 300-foot HD system might prompt designers (or drivers) to "scale back" the system to a 200-foot or even 150-foot range, or might provoke some drivers into disabling their systems entirely.

This short perspective on potential benefits indicates both the great promise of the HD system concept and the many factors that will make this promise a challenge to fulfill. Future research (as described below) on the HD system concept will address these factors, and provide better information for bounding benefits estimates.

<u>R&D Needs</u>

As emphasized, effectiveness estimates based on countermeasure modeling are only theoretical; many important and complex R&D issues need to be addressed successfully before an HD system with effectiveness levels approaching those described above could be deployed. A few of the key R&D needs associated with the HD system concept and technical feasibility are as follows:

* Better quantification of the likely effects of roadway geometry (i.e., curves and hills) on potential system effectiveness.

* Determination of the optimal range and associated transmitter power requirements.

* Determination of optimal bandwidth and frequency of the sensor system to maximize detection while also providing supplemental information on lead-vehicle velocity.

* Assessment of methods of providing lane encoding of lead-vehicle transponder/reflector signals.

* Identification of the most promising sensor candidate based on spatial resolution requirements and ability to minimize false alarms.

* Development of optimized HD system signal processing logic sequences to maximize correct detections and minimize false alarms.

* Overall assessment of technology feasibility, maturity, cost, availability, and practicality

* Design of the HD warning system and its integration with other on-board warning systems.

* Improved characterizations of driver reaction times in the HD system setting.

  Comprehensive analysis of the false alarm problem in terms of the driver interface, including driver reactions to (and acceptance of) various false alarm probabilities.

* Assessment of the degree of compensatory risktaking to be expected after introduction of the system.

* Assessment of the performance of older drivers using the HD system.

* Assessment of the operational robustness of the system; e.g., likely effects of weather, wear, interference, etc.

NHTSA intends to address the research questions listed above in the next phase of its research on countermeasures to rear-end crashes. Accomplishment of the above and related HD system research objectives will transform the formulations of this "front-end analysis" -- i.e., crash reconstructions, functional countermeasure concepts, preliminary technology assessments, and theoretical modeling -- into a set of countermeasure performance specifications that may facilitate industry efforts to develop practical and commercially-viable headway detection systems.

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