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Benefits Estimation of Sensor-Friendly Vehicle and Roadway Cooperative Safety Systems

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ABSTRACT:

An analysis was performed to estimate the potential national costs and benefits of cooperative vehicle and roadway measures to enhance the effectiveness of driver assistance systems. These cooperative measures – query-response communication system, light emitting diode brake light messaging, radar cross section paint striping modifications, fluorescent paint for lane and other marking applications, passive amplifiers on license plates, spatial tetrahedral arrays of reflectors, and in-vehicle corner cubes – are briefly described, along with assumptions that were made regarding performance. For the example lane departure case, the incremental nationwide effectiveness over an autonomous collision avoidance system is estimated and monetized. This was generally determined with respect to annual crash reduction savings, although the technique used allows other mobility benefits to be considered. The marginal benefits of providing each sensor friendly technology were then calculated and aggregated across the various IVI services so that a total marginal benefit was determined for each technology. Complementing this, a method has been established to estimate the magnitude of at- and near-intersection LVNM crashes for these technologies. Together, these methods illustrate national benefits across all crash types (the three-step process) and a more focused means to estimate benefits for a particular crash type (rear end collisions at or near intersections) – and provide a composite approach to the problem.

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INTRODUCTION AND MOTIVATION

Emerging driver-assist systems offer great promise for driver comfort, convenience, and ultimately, safety *(1 – 3)*. Systems such as adaptive cruise control (ACC), forward collision warning (FCW) and avoidance (FCA), and single-vehicle roadway departure (i.e., lane keeping) warning and avoidance are under active research, both in industry *(4 - 7)* and in government. The government focus has been on the socially important safety systems featured in the Intelligent Vehicle Initiative (IVI) *(8 - 9)*.

However, wide-scale market penetration and the realization of safety benefits may take many years. A fundamental hurdle to overcome is operational reliability. Paraphrasing *(3)*, can these systems provide a low enough rate of false positives, false negatives, nuisance alarms, and perceived non-alarms to allow drivers to safely and comfortably use them interoperably, in congestion, and in inclement weather? A possible shortcut to deployment of these systems may be to employ the infrastructure or other vehicles in a cooperative mode, that is, to enhance these otherwise autonomous driver-assist systems to be “sensor friendly”. Objects on the roadway or roadside may somehow be marked -- actively and/or passively -- to enhance the signal-to-clutter, that is, to enhance desired target features within the sensor field-of-regard such that they unambiguously stand out under most conditions. In the end, the operational efficiency would be enhanced and the safety benefits from these emerging driver-assist systems would be realized.

As part of a concept development, assessment and prototyping effort of “sensor friendly” systems, the authors have conducted a systematic assessment of benefits, costs, and deployment requirements through the following three steps:

1. Categorize Technologies. A first step in understanding the benefits and costs of deploying candidate technologies is to abstract and categorize them to a sufficient and uniform granularity such that benefits and costs of the specific enhancement to IVI services are assessed.
2. Estimate Costs, Incremental Effectiveness and Marginal Benefits. The corresponding costs of providing the technology for vehicles and/or highways are then estimated for both Rear End Collision Avoidance Systems (RECAS) and Roadway Departure Avoidance Systems (RDAS).

3. Determine Benefit/Cost Ratio. For each technology candidate, aggregate benefits are ratioed to aggregate costs. Technology candidates are compared on this basis.

For the *benefits* portion of the analysis, categories are initially modeled only to the depth necessary to distinguish common characteristics and categorize crash types, then estimate effectiveness of countermeasure systems incorporating these cooperative technologies. As such, detailed modeling to assess performance of individual technologies was not undertaken. However, for the *cost* portion of the analysis, these categories are discriminated to further detail, wherever possible. This allows for some differentiation between the technologies within each category, presuming that all technologies within the category are identically effective. Hence, in the end the benefits calculation ranks categories, then the cost calculation ranks costs. Fusing cost and benefits can lead to a ranking of all technologies, although some of the distinction will be imperfect due to the lower granularity of the benefits estimation than with the cost.

Despite these limitations in data and modeling fidelity, steps 1 – 3 provide a framework appropriate for macroscopic economic benefit analysis for vehicle-roadside cooperative IVI systems. The authors describe this framework through an illustrative application to the RDAS problem, although it can be generalized to RECAS, which was done by the authors. (The authors readily acknowledge that since the technique would be sensitive to assumptions of the values for many of the individual factors; hence, this is represented as only a base and illustrative case. Further on-road experiments coupled with manufacturing feasibility studies are necessary to more precisely understand benefits and costs.)

Additionally, as a means to further illustrate how cooperative vehicle-roadway systems may be evaluated for specific crash types and scenarios, the authors have applied a complimentary and more detailed method to estimate costs and benefits in the application of "sensor friendly" features to the lead vehicle not moving (LVNM) RECAS scenario at or near intersections. Taken in sum, these two methods illustrate national benefits across all crash types (the three-step process) and a more focused means to estimate benefits for a particular crash type (rear end collisions at or near intersections) – and provide a composite low-plus-high fidelity approach to the problem.

TECHNOLOGY CATEGORIZATION

For purposes of abstracting operational performance based on common characteristics, specific sensor-friendly technologies under consideration for further development and testing are grouped into three general categories: messaging, lane definition and tagging. These are listed in Table 1, along with a listing of constituent technologies and crash types which the categories and technologies are intended to address. “Sensor friendly” technologies are summarized below, but described to further detail in *(10).*

Table 1. Categorization of Sensor Friendly Technologies

CATEGORY	TECHNOLOGY	CRASH TYPE(S) PRIMARILY ADDRESSED
Messaging	• Query-Response Communication System (QRCS) • Light Emitting Diode Brake Light Messaging (LEDBM)	Rear End
Lane Definition	• Radar Cross Section Paint Striping Modifications (RadarP) • Fluorescent Paint for Lane and Other Marking Applications (FluorP)	Lane Departure and Curve Warning[1]
Tagging	• Passive Amplifiers on License Plates (PALP) • Roadside Corner Cube Markings: Spatial Tetrahedral Arrays of Reflectors (STAR) • In-Vehicle Corner Cubes (IVCC)	Rear End

Query-Response Communication System (QRCS)

A QRCS system is intended primarily to address rear end collisions. It consists of two main elements: (a) a passive tag, which transponds a signal when "hit" with an interrogating signal, and also (b) the source of the response signal. It is primarily conceived to operate at the set of near-77 GHz frequencies of forward radar sensors; as such, the system would need no additional transmitter or receivers. According to *(11),* an in-band algorithm and coherent data detection permits the tag to be passed through the Doppler processing but at a signal intensity below the clutter level; hence, the response signal can then be coherently detected within the existing automotive radar

[1] The lane definition function may also aid a rear end crash countermeasure target selection algorithm by determining and eliminating out-of-path objects, which can be simply regarded as potential targets not within the lane of the subject vehicle.

processor. The response signal is matched with the Doppler return to identify the target, then be used to warn the driver.

Hence, the subject vehicle would sense the vehicle in front. If the vehicle in front has a tag, then the available additional information would be sent back. So if the tag was tied to an in-vehicle data bus, and the forward vehicle had accelerometers, yaw rate sensors, and possibly other state information sensors, that information could be communicated to the threat assessment processors on board the subject vehicle.

Radar Cross Section Paint Striping Modifications (RadarP)

The RadarP may address both lane departure and curve warning. Secondarily, it addresses rear end collisions. The function is the same for both crash countermeasure application -- to delineate lane boundaries. That delineation could serve as a replacement/supplement for vision-based systems, or it could serve as a means to identify and reject out-of-lane clutter. The technology may support the increased effectiveness of these crash types, as it provides information that could be fused with autonomously-sensed information, or even information already filtered by data from GPS/map database. A further contingency to its effectiveness would be azimuthal discrimination, which is a debatable issue until the effective range for which such a system will work is determined.

The RadarP system would consist of a low density of RCS-modifying additives pre-mixed with the paint binder or thermoplastic conventionally used in striping.

Fluorescent Paint for Lane and Other Marking Applications (FluorP)

The problem addressed, operational concept and issues and concern with FluorP are very much like RadarP, with the exceptions that a near infrared (NIR) detector and processing scheme must be provided with each equipped vehicle. In the FluorP concept, instead of RCS-modifying additives, additional pigmentation that fluoresces in the NIR would be inserted into the paint binder or thermoplastic or into the glass beads. A stimulating light source (e.g., a visible red diode laser) and a detector for the fluorescence (e.g., an infrared sensitive photodiode) must be provided.

Passive Amplifiers on License Plates (PALP)

The PALP technology addresses rear end collisions. A PALP consists of a visually transparent layer of radar cross section (RCS)-modifying superstrate which consists of the outer layer of license plates. With PALP, the RCS signature is modified such that the forward vehicle (with a rear plate) is presented to the subject vehicle as a near-point source of uniform and high RCS over a wide (plus- or minus-45 degree) azimuth. With PALP technologies widely deployed, subject vehicles equipped with FCW or FCA systems would be able to reliably pick out forward cars in curves, adjacent lanes or in inclement weather (which might introduce road spray that could otherwise extinguish low RCS from forward vehicles at certain relative yaw angles).

Roadside Corner Cube Markings: Spatial Tetrahedral Arrays of Reflectors (STAR) and In-Vehicle Corner Cubes (IVCC)

Both the STAR and IVCC concepts address rear end collisions. Unique patterns of corner cubes are the hallmark feature, with the STAR configuration being longitudinal to take advantage of the normal 0.5- to 1-meter range resolution typically found with an automotive radar vs. several feet of cross-range (lateral) resolution available at ranges approaching the 150 m maximum normally found with these radars. Hence, a STAR configuration could nominally consist of a cantilevered pole projecting from an overhead sign panel or along the side of a road. Upon that pole a configuration of corner cubes would rest, each with a well-known RCS, such that a sequence (e.g., three corner cubes) would signal the presence of a potentially confusing “clutter” signature (e.g., bridge abutment, sign panel).

In the IVCC application of corner cubes, a corner cube may be used in much the manner as a PALP, although the azimuthal extent of such a signature would be considerably less.

COST, INCREMENTAL EFFECTIVENESS AND MARGINAL BENEFIT ESTIMATES OF ROADWAY DEPARTURE AVOIDANCE SYSTEMS (RDAS)

Effectiveness of Cooperative RDAS Systems

For a quantitative assessment of the marginal benefit of RDAS, assume that the technologies within the Lane Definition category of Table 1, RadarP or FluorP, are used to provide cooperative communication between the roadway and vehicle such that the effectiveness of RDAS (defined as lane departure and curve warning) is increased. The cooperative communication would enable vehicles to determine their precise location with respect to the road by sensing lane markings with additional sensors on the vehicle. This feature could either assist vision- or GPS-based RDASs by providing supplementary information for instrumented roadway segments and environment where these sensors cannot accurately or reliably determine current lane position.

The marginal benefit can be calculated as:

$$B_j = (V_j)\,[(E1)\,(P1) + (E2_j)\,(P2)]\,(A)\,(L) - (V_j)\,(F)\,(C_j) - (M_j)\,(D1_j + D2_j) \qquad (1)$$

where:

B_j = Marginal annual benefits of deploying technology “j” to enhance RDAS, to include curve overspeed.

V_j = Proportion of the vehicle fleet equipped with technology “j” used in conjunction with a RDAS in reducing roadway departure crashes.

$E1_j$ = Marginal effectiveness of technology “j” when used in conjunction with a lane departure system in reducing roadway departure crashes

$E2_j$ = Marginal effectiveness of technology “j” when used in conjunction with a curve warning system in reducing roadway departure crashes

P1 = Annual number of roadway departure crashes that could be addressed through cooperative technology for lane departure crashes

P2 = Annual number of roadway departure crashes that could be addressed through cooperative technology for speed/curve crashes.

M_j = Miles of roadway where technology "j" is deployed

A = Average cost of each RD crash avoided

L_j = Life of the vehicle with technology "j"

F = Size of vehicle fleet

C_j = Unit cost of technology "j" per vehicle

D1 = Unit cost of deploying continuous pavement marking technology

D2 = Unit cost of deploying pavement marking technology to provide advance information for curves

The total crash population for RD crashes was recently recalculated by Najm *(12),* based upon1998 GES data, to be about 938,000 crashes per year. From *(12)* approximately 90,000 lane change crashes each year are attributed to "drifting", which is distinguished from "loss of control". Both these crashes could also be countered by a cooperative RDAS using RadarP or FluorP.

The following values are assumed to estimate marginal benefit for the combined RDAS technologies: V = .30, E1 = .03, E2 = .04 (assuming that approximately 30% of RD crashes involving high speeds at curves could be avoided through use of this technology), P1 = 90,000 crashes, P2 = 938,000 crashes, A = $32,700 *(13),* F =

150,000,000 vehicles, C = $40 per vehicle (assuming that only minor changes to the RD system's processing and driver interface would be needed), D1 = D2 = $10 per mile incremental cost for continuous markings, and M = 2 million miles of sensor friendly pavement markings.

Assume also that the total value of SVRD crashes: $30.7 Billion *(14).* Hence, assuming 30% market penetration, the benefit is $2.1 billion.

Baseline Case: Effectiveness of Autonomous RDAS Systems

It is interesting to compare the E1 = 0.03 and E2 = 0.04 values with an effectiveness estimate for the baseline autonomous RDAS. In *(14),* roadway departure (RD) collisions are separated into drift off road vs. too fast in a corner. For the first type, only crashes caused by driver inattention and "driver relinquishes steering control" could be prevented by a warning system; collisions involving alcohol may not be preventable if the driver is too intoxicated to react, and collisions involving vehicle failure are not avoidable by a warning system. After these exclusions, 24% of all road departure crashes are applicable; in heavy trucks, the number is 53%, because of the higher percentages of crashes due to drowsiness.

Next, the width of the shoulder has to be taken into account. For instance, 40% of all RD crashes occur where the shoulder width is 0-3 feet, where a warning system (according to simulations) would only have a 20% effectiveness rate. Averaging over all shoulder widths, the total effectiveness is estimated at 56%. For trucks, who stay on bigger roads, but who have a lower margin of error, the percentage is 63%. Discounts due to adverse environmental conditions, missing lane boundaries and for systems that shut down at lower speeds (e.g., according to *(14)* 24% of crashes occur at speeds less than 35 mph) can be applied to reduce these factors.

The baseline effectiveness could be similarly estimated via Equation 1, with simple substitution of autonomous values rather than cooperative values (e.g., E1 = 56% for cars, D1 = D2 = 0). The authors do not do this due to uncertainties in L_j (life of the vehicle with technology “j”) and C_j (unit cost of technology “j” per vehicle). This information is proprietary to RDAS vendors and vehicle OEMs, and it varies widely from system to system, as does the effectiveness. Definition of these quantities, however, will undoubtedly happen as RDAS systems are widely marketed to the driving public.

FOCUSED BENEFITS ANALYSIS: LVNM CRASH SCENARIOS AT OR NEAR INTERSECTIONS

The methodology employed in this analysis combines ideas from a number of authors, most notably Najm and Burgett, and Tijerina. It begins with an assessment of broad-scale "societal benefits"; that method is described in detail in *(15)* and *(16)*, with data sources stemming especially from *(15)* and also from *(12,17)*. It infuses elements of a reliability analysis reported in *(18)*, originally intended to assess the efficacy of side object detection systems, but adapted here for the FCW problem. In the end cost savings are determined based on data from *(19)*. From these cost savings, the investment decision on whether these cooperative features could be justifiably implemented can presumably be made. Hence, from the investment decision-making perspective, this analysis is end-to-end, beginning with effectiveness estimates and ending with total costs.

The three main components -- estimation of societal benefits, reliability analysis, and the roll-up of lives saved -- are described below. However, there are provisos, namely:

- an assumption that the LVNM case is the "low hanging fruit" -- and therefore the focus of this benefits analysis; and
- engineering judgement on the degree of effectiveness of FCW measures.

To address all these assumptions, this section is further divided into a discussion of the size of the LVNM-at-intersection focus area, and on FCW effectiveness, followed by a subsection addressing the fusion of societal benefit estimation and reliability analysis, and concluding with the results of the analysis. Intersection and near-intersection scenarios for highest-value FCW cooperative countermeasures will be presented as the basis for the subsequent results that sensor friendly FCW offers tangible, monetizable benefits.

Problem Size

In *(20)* the highest-frequency LVNM crash scenarios were identified, based primarily on National Accident Sampling System (NASS) General Estimates System (GES) data for 1997. The proportion of LVNM crashes is high --10,009 LVNM crashes from a sample of 55,562 represented crashes[2] *(21).*

The resultant four most frequent LVNM scenarios are listed in Table 2, with totals and frequencies given in parentheses. It is important to note that nearly 75% of all LNVM crashes fall within the first two scenarios. For this reason, we will focus on “near intersection” and “midblock” *non-freeway* scenarios, which are argued in *(20)* to be mostly near intersections, in estimating the effectiveness of cooperative systems.

[2] We recognize that a LVNM crash may involve three or more vehicles, and actually, multiple LVNM’s. However, we consider only the initial rear-end collision because we presume crash countermeasures to be most effective in warning and control up to the crash.

Table 2. Four Most Frequent LVNM Scenarios (1997 NASS GES Data)

SCENARIO 1: "NEAR INTERSECTION"	SCENARIO 2: "MIDBLOCK"	SCENARIO 3: "FREEWAY"	SCENARIO 4: "NON-INTERSECTION JUNCTION"
The struck vehicle stopped at or near an intersection. (4,274; 43%)	The struck vehicle stopped due to traffic congestion or at the end of a long queue of vehicles waiting to pass through an intersection. (3080; 31%)	The struck vehicle stopped on a freeway. (1828; 18%)	The struck vehicle stopped at a non-intersection junction, e.g., a junction between a regular roadway and a driveway, an alleyway, or a ramp, or an unknown type of junction. (827; 8%)
Scenario 1.1: stopped at or near a signal (2,539; 25%) *Scenario 1.2:* stopped at or near a stop sign (542; 5%) *Scenario 1.3:* stopped 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; 11%)	(A more precise description of this scenario is that the struck vehicle stopped on a non-freeway travel lane, but was not proximate to any junction, e.g., an intersection, a ramp, a driveway, an alleyway, railroad crossing, etc. The current title of the scenario is actually an inference made based upon this more precise description.)	*Scenario 3.1:* on an urban freeway (881; 9%) *Scenario 3.2:* on a rural freeway (231; 2%) *Scenario 3.3:* on an urban/rural freeway (716; 7%)[3]	

Effectiveness Estimates

Estimates of performance for each of these cooperative measures are given in Table 3 below. Performance is defined as the difference in the collision avoidance reliability, or probability of crash avoiding behavior, of a driver using Sensor Friendly Vehicle and Roadway (SFVR) collision countermeasures; this is labeled R_{SFVR}.

It is important to note in advance that these estimates hinge on assumptions on LVNM crash-avoiding reliability R_{CAS} of a driver using autonomous collision countermeasures, that is, countermeasures without the use of SFVR.

[3] The freeways on which the crashes occurred run through both urban and rural areas in the Primary Sampling Unit (which is the basic unit of geographical area for accident reporting). The GES infers this based on the Police Accident Reports, which in general report only the freeway identity and the location on the freeway but do not in general indicate whether the accident scene is located on an urban or a rural section of the freeway.

From previous work *(15)* the "dry pavement" R_{CAS} is assumed to be 0.971, and the "wet pavement" R_{CAS} is assumed to be 0.960. However, because the preponderance of crashes occur with the dry pavement case, the composite R_{CAS} is 0.969. Note that this sets R_{CAS} values to relatively near unity, leaving small margin for R_{SFVR}. It also ignores that the delta in reliability, or R_{SFVR}, afforded by SFVR features significantly may abet the system to the extent that user acceptance and market penetration are increased. In order to understand potential benefits -- and sensitivities -- two cases are assumed:

- Status Quo Case: Simply extends other investigators' assumptions about R_{CAS} *(12,15,18)*. Market penetration and system effectiveness is as assumed in *(15)*, with $R_{CAS} + R_{SFVR}$ now representing the total CAS reliability.
- Sensitivity Test Case: Assumes that the introduction of CAS will not only lead to riskier driver behavior (i.e., we reduce R_{driver}), but that *(15)* overstates the stand-alone reliability of CAS (i.e., we reduce R_{CAS}).

For these cases, estimating these R_{SFVR} quantities is difficult. Because these are all candidate and, at present, notional systems for development, performance judgements are currently subjective. The Composite R_{SFVR} for the Sensitivity Test Case is set at a factor of 4 increase of the values used in the Status Quo Case, under the general assumption that with reduced R_{driver} and R_{CAS}, SFVR measures could feasibly have a greater contribution. This assumption and the specific values used are strictly judgement calls; however, the methodology is applicable to any revised set of parameters. Therefore, a case built with objective evidence can eventually be established.

Table 3. SFVR Reliability Estimates

SFVR System	Status Quo Case: Dry Pavement R_{SFVR}	Status Quo Case: Wet Pavement R_{SFVR}	Status Quo Case: Composite R_{SFVR}	Sensitivity Test Case: Composite R_{SFVR}	Comments
LEDBM	0.02	0.02	0.02	0.08	LEDs may provide supplemental state information (accelerations and velocities) of the car in front, providing higher confidence to information from forward ranging sensors. LEDs would work the same regardless of the pavement surface condition.
STAR and IVCC	0.005	0.0025	0.005	0.02	Corner cubes would mark occasional high RCS clutter objects (electroliers, traffic control devices including signals, overhead panels and signs, other vehicles), so these can be rejected as threats. Clutter is increased by multipath (and other) returns due to wet surfaces.
PALP and QRCS	0.02	0.02	0.02	0.08	Vehicle target/threat signatures would be separated from non-threat clutter objects, aiding in threat assessment. Clutter is increased by multipath (and other) returns due to wet surfaces.
RadarP and FluorP	0.02	0.01	0.02	0.08	In-lane determination can be made using unambiguous signatures from pavement markings. Clutter is increased by multipath (and other) returns due to wet surfaces.

Fusion of Societal Benefit Estimation and Reliability Analysis

Tijerina has applied what he terms "standard reliability" analysis to estimate the effectiveness of autonomous lane change CAS *(18)*. His formulation and approach are interesting, especially when considered in tandem with the Najm and Burgett *(15)* approach. The R_{CAS} for LVNM from *(15)* can be fused with a reformulation of Tijerina's reliability analysis to include the additional effectiveness of R_{SFVR},

$$R_{composite} = U_{driver}R_{driver} + U_{CAS}(R_{CAS} + R_{SFVR}) + U_{series}(R_{CAS} + R_{SFVR})\,R_{driver} + U_{parallel}(1 - (1 - (R_{CAS} + R_{SFVR}))(1 - R_{driver})). \qquad (2)$$

In the equation above, $R_{composite}$ is the reliability of the system, with four contributing terms associated with U defined in *(18)* as proportions of use in the driving population using CAS, relating to general attitudes of cautious skepticism (U_{driver} = 0.75, U_{CAS} = 0, U_{series} = 0, $U_{parallel}$ = 0.25), cautious acceptance (U_{driver} = 0.25, U_{CAS} = 0, U_{series} = 0, $U_{parallel}$ = 0.75), ideal acceptance (U_{driver} = 0, U_{CAS} = 0, U_{series} = 0, $U_{parallel}$ = 1), and complacent acceptance (U_{driver} = 0.125, U_{CAS} = .125, U_{series} = .125, $U_{parallel}$ = 0.625). These numbers are simply normative values, but they make intuitive sense; as acceptance grows, so does the use of CAS, especially as an independent and parallel -- or driver assist -- input. Tijerina did not presume to know the attitude of the population outside of assigning nominal numbers to represent four potential prevailing degrees of acceptance, and neither is it presumed here; instead, $R_{composite}$ parametrically calculated using Tijerina's mixes of U.

Other than the existence of the delta term R_{SFVR}, there are several other differences from Tijerina's reliability methodology: for each potential collision event, the independent (without CAS) driver reliability, or probability of crash-avoidance behavior, R_{driver}, is directly determined; R_{driver} is 0.793 for the dry pavement case, 0.930 for the slippery pavement case, and the composite R_{driver}, is 0.798, based on VMT in each pavement condition[4]. From R_{driver}, R_{CAS} is directly determined by the relationship E = (R_{CAS} - R_{driver})/(1 - R_{driver}), where E is the system effectiveness, with values determined by the crash-imminent scenarios and kinematic modeling reported in [1].

Results

Status Quo Case

Using Equation (2) , $R_{composite}$ is calculated for each of the four degrees of U, for each of the five SFVR technologies, and for wet pavement, dry pavement and a composite condition. Then, the same calculation is performed without R_{SFVR}. The differences in the $R_{composite}$ are multiplied by 428,500 relevant LVNM crashes used in *(15)* and the percentage of at- or near-intersection crashes (shown in Table 2). The result is the total number and percentage of crashes prevented with the use of SFVR devices over autonomous CAS within the constraint of the scenarios we considered.

[4] Note that as reported in [1] R_{driver}, is higher in the slippery condition than in the dry pavement case. We conjecture that if true, this is because the driver is more careful under wet conditions.

Using the comprehensive (to include the value of injury and of lives saved) from recent work reported in (*19)*, the number of crashes prevented is then multiplied by that amount, $38,960[5]. The result is the monetary savings due to our estimates of reliability improvement due to the addition of SFVR collision countermeasure devices. This is summarized in Table 4 for the composite (combined wet and dry pavement) case.

Table 4. Status Quo Case: Calculated Benefits from SFVR Collision Countermeasure Systems

Degree of Acceptance	SFVR Technology	Number of Crashes Prevented	Monetary Savings per Year ($)
Cautious Skepticism	LEDBM	15,855	558,000,000
	STAR and IVCC	15,538	547,000,000
	PALP and QRCS	15,855	558,000,000
	RadarP and FluorP	15,855	558,000,000
Cautious Acceptance	LEDBM	17,440	614,000,000
	STAR and IVCC	17,440	614,000,000
	PALP and QRCS	17,440	614,000,000
	RadarP and FluorP	17,440	614,000,000
Ideal Acceptance	LEDBM	1902	67,000,000
	STAR and IVCC	1902	67,000,000
	PALP and QRCS	1902	67,000,000
	RadarP and FluorP	1902	67,000,000
Complacent Acceptance	LEDBM	19,343	681,000,000
	STAR and IVCC	19,343	681,000,000
	PALP and QRCS	19,343	681,000,000
	RadarP and FluorP	19,343	681,000,000

The right-most column, or monetary savings, provides a breakeven point for an investment decision on whether to implement SFVR cooperative features, depending on the technology used and assumptions on the degree of acceptance by drivers in using CAS. This may be modified due to the time value of money associated with the installation of the necessary infrastructure; moreover, other factors such as the potential acceleration of market introduction or penetration due to the incremental increase in reliability of SFVR-based systems are not calculated.

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[5] This amount presumes that the severities LVNM crashes within our scenario to correspond exactly to the composite severity of LVNM. Although it is not likely to be the case, since at- or near-intersection crashes are generally at lower speeds and therefore at lower severity than, for example, highway LVNM crashes, we still use it with the explicit understanding that the resulting cost of crashes is likely to be an unknown amount less than we calculate.

Finally, only intersection and near-intersection cases are examined; as noted up front additional benefits would accrue by extending this analysis to other cases.

Sensitivity Test Case

The same methodology used in the status quo case was applied, with the differences being that R_{driver} and R_{CAS} are each 5% less than with the Status Quo Case, also allowing room for insertion of the values in the "Sensitivity Test Case: Composite R_{SFVR}" (or second right-most) column of Table 3 to Equation (2). Results are shown in Table 5.

Table 5. Sensitivity Test Case: Calculated Benefits from SFVR Collision Countermeasure Systems

Degree of Acceptance	SFVR Technology	Number of Crashes Prevented	Monetary Savings per Year ($)
Cautious Skepticism	LEDBM	19,977	703,000,000
	STAR and IVCC	18,392	647,000,000
	PALP and QRCS	19,977	703,000,000
	RadarP and FluorP	19,977	703,000,000
Cautious Acceptance	LEDBM	24,734	870,000,000
	STAR and IVCC	24,734	870,000,000
	PALP and QRCS	24,734	870,000,000
	RadarP and FluorP	24,734	870,000,000
Ideal Acceptance	LEDBM	6342	223,000,000
	STAR and IVCC	6342	223,000,000
	PALP and QRCS	6342	223,000,000
	RadarP and FluorP	6342	223,000,000
Complacent Acceptance	LEDBM	29,490	1,038,000,000
	STAR and IVCC	29,490	1,038,000,000
	PALP and QRCS	29,490	1,038,000,000
	RadarP and FluorP	29,490	1,038,000,000

Summary

A method has been established to estimate the magnitude of at- and near-intersection LVNM crashes for four functional categories of cooperative countermeasure technologies: LEDBM, STAR and IVCC, PALP and QRCS, and RadarP and FluorP. Populating this with certain assumptions and values have yielded yearly monetary benefits ranging from $67 – 681 million, depending on the degree of societal acceptance assumed, set at four discrete levels varying from "cautious skepticism" through "complacent acceptance".

Furthermore, yearly monetary benefits have been calculated by increasing estimates of SFVR effectiveness (by a factor of four), with a concomitant variation in the reliability of drivers using CAS technology (diminishing it by 5% off a scale of 100% effectiveness), as well as CAS technology itself (again, with the same 5% decrement). Using this, the yearly monetary benefit with the alternate set of assumptions now varies from $223 - 1,038 million. This points toward the sensitivity of this method to assumptions about CAS effectiveness, driver risk-taking with CAS, and particularly, effectiveness of the underlying SFVR technology.

In both cases, the benefits are seen to potentially be quite significant -- enough, possibly, to justify public and private investment in SFVR adjuncts to in-vehicle CAS systems. Specifically, with a means to estimate of the monetary benefits due to SFVR systems, a broad-scale estimate of the maximum investment to implement SFVR features can be given, especially once engineering methods are fine-tuned. To emphasis, these initial numbers are subject to our initial estimates of SFVR effectiveness, along with the available estimates from others on autonomous CAS effectiveness.

CONCLUDING COMMENTS

A key assumption in the above example is the assumed penetration of cooperative RECAS vehicles. Moreover, the above discussion relates to the use of the technology for only one purpose. While the incremental benefits may be useful in justifying a particular technology as “cost beneficial”, a more meaningful measure is the aggregated benefits and aggregated costs of deploying the technology to support multiple applications.

The ratio is driven by two factors: the applicability of these systems to broader issues than the marginal improvements over vision-based sensors, and the in-vehicle costs required to perform reliable sensing. The question of applicability seems clear: these systems can certainly perform many more functions, but must be considered in the light of other ongoing, partially-competing, developments. The question of in-vehicle costs is one of the central questions of cooperative collision avoidance and warning systems, and one which the authors have defined two different, complimentary means to analyze. The next step, clearly, is to pursue technically feasible concepts, then reiterate on the initial top-level cost and effectiveness estimates to arrive at system benefits and a joint public/private decision for deployment of these life saving technologies.

REFERENCES

1. Shladover, Steve E., "Review of the State of Development of Advanced Vehicle Control Systems (AVCS), *Vehicle System Dynamics*, Vol. 24, pp. 551 - 595, 1995.
2. "Synthesis Report: Examination of Target Vehicular Crashes and Potential Countermeasures." Research Report, U.S. Department of Transportation, DOT-VNTSA-NHTSA-95-4, Volpe National Transportation Center, June 1995.
3. Godbole, Datta N., Raja Sengupta, James Misener, Natalia Kourjanskaia, and James Bret Micheal, "Benefit Evaluation of Crash Avoidance Systems", Presented at TRB Annual Meeting, 1998.
4. Ioannou P.A., and C.C. Chien, "Autonomous Intelligent Cruise Control", *IEEE Transactions on Vehicular Technology*, Vol. 43, No. 4, 1994, pp. 1125 - 1135.
5. Reichart G., R. Haller, and K. Naab, "Driver Assistance: BMW Solutions for the Future of Individual Mobility", In *Proceedings of ITS World Congress*, Orlando, October 1996.
6. Watanabe T., Kishimoto N., Hayafune K., Ymada K., Maede N., "Development of an Intelligent Cruise Control System", Misubishi Motors Corporation, Japan.
7. Jerry Woll, "Radar Based Adaptive Cruise Control for Truck Applications", SAE Paper No. 973184, Presented at *SAE International Truck and Bus Meeting and Exposition*, Cleveland, Ohio, November 1997.
8. "Forward-Looking Collision Warning System Performance Guidelines," Research report prepared by Frontier Engineering for NHTSA Office of Crash Avoidance Research, December, 1996.
9. United States Department of Transportation Systems Joint Program Office. "Intelligent Vehicle Initiative Business Plan." November, 1997.
10. James A. Misener, Chuck Thorpe, Ron Hearne, Lee Johnson, Andrew C. Segal, "Enhancing Driver-Assist Sensors: Background And Concepts For Sensor-Friendly Vehicles And Roadways", *Proceedings of the ITSA Annual Meeting,* Washington D.C., April 1999.
11. Chiochetti, J., "Improving Vehicle Radar", *ITS World*, March/April 2000, pp 22 - 23.
12. Najim, W. G., Wiacek, C.J., and Burgett, A.L., "Identification of Precrash Scenarios for Estimating the Safety Benefits of Rear-End Collision Avoidance Systems," *Proceedings 5th World Congress on Intelligent Transport Systems*, 12 – 16 October, 1998, Seoul, Korea.

13. Wang, J-S, Knipling, R.R., and Blincoe, L.J. "The Dimensions of Motor Vehicle Crash Risk", *Journal of Transportation and Statistics*, Vol 2, No 1, May 1999.

14. D. Pomerleau and C. Thorpe, “Performance Specification Development for Roadway Departure Collision Avoidance Systems: Final Report”, in review.

15. Najm, W.G., and Burgett, A. L., "Benefits Estimation for Selected Collision Avoidance Systems", *Proceedings of the 4th World Congress on Intelligent Transport Systems*, Berlin, Germany, Washington D.C: Intelligent Transportation Society of America

16. Datta N. Godbole, Raja Sengupta, James Misener, Natalia Kourjanskaia and James B. Michael (August 1997) “Benefit Evaluation of Crash Avoidance Systems” Transportation Research Record, No. 1621 (Safety and Human Performance), 1998.

17. Wiacek, C.J., and Najm, W.G, “Driver/Vehicle Characteristics in Rear-End Precrash Scenarios Based on the General Estimates System (GES)”, *SAE International Congress and Exposition*, March 1 – 4 1999, SAE 1999-01-0817.

18. Tijerina, L., and Garrott, W.R. "Recommended performance of a lane change crash avoidance system [CAS] driver interface with special reference to system reliability." *Proceedings of the 4th World Congress on Intelligent Transport Systems*, Berlin, Germany, Washington D.C: Intelligent Transportation Society of America.

19. Wang, J-S, Knipling, R.R., and Blincoe, L.J. "The Dimensions of Motor Vehicle Crash Risk", *Journal of Transportation and Statistics*, Vol 2, No 1, May 1999.

20. James A. Misener, Hsiao-Shen Jacob Tsao, Bobsob Song, Aaron Steinfeld (January 2000), “The Emergence of a Cognitive Car Following Driver Model with Application to Rear-End Crashes with a Stopped Lead Vehicle" (Paper No. 00-1491) in *Proceedings of the 79th Annual Meeting of the Transportation Research Board*, Washington D.C., 2000.

21. National Accident Sampling System (NASS) General Estimates System (GES), Department of Transportation, National Highway Traffic Safety Administration, National Center for Statistics and Analysis, Washington, D.C. 20590.

LIST OF TABLES

Table 1. Categorization of Sensor Friendly Technologies

CATEGORY	TECHNOLOGY	CRASH TYPE(S) PRIMARILY ADDRESSED
Messaging	• Query-Response Communication System (QRCS) • Light Emitting Diode Brake Light Messaging (LEDBM)	Rear End
Lane Definition	• Radar Cross Section Paint Striping Modifications (RadarP) • Fluorescent Paint for Lane and Other Marking Applications (FluorP)	Lane Departure and Curve Warning[6]
Tagging	• Passive Amplifiers on License Plates (PALP) • Roadside Corner Cube Markings: Spatial Tetrahedral Arrays of Reflectors (STAR) • In-Vehicle Corner Cubes (IVCC)	Rear End

[6] The lane definition function may also aid a rear end crash countermeasure target selection algorithm by determining and eliminating out-of-path objects, which can be simply regarded as potential targets not within the lane of the subject vehicle.

Table 2. Four Most Frequent LVNM Scenarios (1997 NASS GES Data)

SCENARIO 1: "NEAR INTERSECTION" The struck vehicle stopped at or near an intersection. (4,274; 43%)	SCENARIO 2: "MIDBLOCK" The struck vehicle stopped due to traffic congestion or at the end of a long queue of vehicles waiting to pass through an intersection. (3080; 31%)	SCENARIO 3: "FREEWAY" The struck vehicle stopped on a freeway. (1828; 18%)	SCENARIO 4: "NON-INTERSECTION JUNCTION" The struck vehicle stopped at a non-intersection junction, e.g., a junction between a regular roadway and a driveway, an alleyway, or a ramp, or an unknown type of junction. (827; 8%)
Scenario 1.1: stopped at or near a signal (2,539; 25%) *Scenario 1.2:* stopped at or near a stop sign (542; 5%) *Scenario 1.3:* stopped 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; 11%)	(A more precise description of this scenario is that the struck vehicle stopped on a non-freeway travel lane, but was not proximate to any junction, e.g., an intersection, a ramp, a driveway, an alleyway, railroad crossing, etc. The current title of the scenario is actually an inference made based upon this more precise description.)	*Scenario 3.1:* on an urban freeway (881; 9%) *Scenario 3.2:* on a rural freeway (231; 2%) *Scenario 3.3:* on an urban/rural freeway (716; 7%)[7]	

[7] The freeways on which the crashes occurred run through both urban and rural areas in the Primary Sampling Unit (which is the basic unit of geographical area for accident reporting). The GES infers this based on the Police Accident Reports, which in general report only the freeway identity and the location on the freeway but do not in general indicate whether the accident scene is located on an urban or a rural section of the freeway.

Table 3. SFVR Reliability Estimates

SFVR System	**Status Quo Case: Dry Pavement R_{SFVR}**	**Status Quo Case: Wet Pavement R_{SFVR}**	**Status Quo Case: Composite R_{SFVR}**	**Sensitivity Test Case: Composite R_{SFVR}**	**Comments**
LEDBM	0.02	0.02	0.02	0.08	LEDs may provide supplemental state information (accelerations and velocities) of the car in front, providing higher confidence to information from forward ranging sensors. LEDs would work the same regardless of the pavement surface condition.
STAR and IVCC	0.005	0.0025	0.005	0.02	Corner cubes would mark occasional high RCS clutter objects (electroliers, traffic control devices including signals, overhead panels and signs, other vehicles), so these can be rejected as threats. Clutter is increased by multipath (and other) returns due to wet surfaces.
PALP and QRCS	0.02	0.02	0.02	0.08	Vehicle target/threat signatures would be separated from non-threat clutter objects, aiding in threat assessment. Clutter is increased by multipath (and other) returns due to wet surfaces.
RadarP and FluorP	0.02	0.01	0.02	0.08	In-lane determination can be made using unambiguous signatures from pavement markings. Clutter is increased by multipath (and other) returns due to wet surfaces.

Table 4. Status Quo Case: Calculated Benefits from SFVR Collision Countermeasure Systems

Degree of Acceptance	SFVR Technology	Number of Crashes Prevented	Monetary Savings per Year ($)
Cautious Skepticism	LEDBM	15,855	558,000,000
	STAR and IVCC	15,538	547,000,000
	PALP and QRCS	15,855	558,000,000
	RadarP and FluorP	15,855	558,000,000
Cautious Acceptance	LEDBM	17,440	614,000,000
	STAR and IVCC	17,440	614,000,000
	PALP and QRCS	17,440	614,000,000
	RadarP and FluorP	17,440	614,000,000
Ideal Acceptance	LEDBM	1902	67,000,000
	STAR and IVCC	1902	67,000,000
	PALP and QRCS	1902	67,000,000
	RadarP and FluorP	1902	67,000,000
Complacent Acceptance	LEDBM	19,343	681,000,000
	STAR and IVCC	19,343	681,000,000
	PALP and QRCS	19,343	681,000,000
	RadarP and FluorP	19,343	681,000,000

Table 5. Sensitivity Test Case: Calculated Benefits from SFVR Collision Countermeasure Systems

Degree of Acceptance	SFVR Technology	Number of Crashes Prevented	Monetary Savings per Year ($)
Cautious Skepticism	LEDBM	19,977	703,000,000
	STAR and IVCC	18,392	647,000,000
	PALP and QRCS	19,977	703,000,000
	RadarP and FluorP	19,977	703,000,000
Cautious Acceptance	LEDBM	24,734	870,000,000
	STAR and IVCC	24,734	870,000,000
	PALP and QRCS	24,734	870,000,000
	RadarP and FluorP	24,734	870,000,000
Ideal Acceptance	LEDBM	6342	223,000,000
	STAR and IVCC	6342	223,000,000
	PALP and QRCS	6342	223,000,000
	RadarP and FluorP	6342	223,000,000
Complacent Acceptance	LEDBM	29,490	1,038,000,000
	STAR and IVCC	29,490	1,038,000,000
	PALP and QRCS	29,490	1,038,000,000
	RadarP and FluorP	29,490	1,038,000,000