A REAR END COLLISION WARNING SYSTEM FOR TRANSIT BUSES

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ABSTRACT

Rear impact crashes are the most frequent type of bus accidents. Transit buses are particularly susceptible to rear impact collisions because of their frequent stops, which often occur in traffic lanes. The majority of bus collisions occur while the bus is decelerating or stopped. The preponderance of crashes occur with buses stopped during daylight hours, in good weather conditions, while traversing a straight path, and with the striking vehicle attempting no avoidance or corrective action.

To respond to this surprising set of crash conditions, General Dynamics, in partnership with the Ann Arbor Transit Authority (AATA), developed a Rear-Impact Collision Warning System (RICWS) based on our premise that following drivers were either being distracted or simply not paying attention. To determine the following drivers' behaviors behind transit buses, General Dynamics first conducted a series of field collections using a recording system, digital video, and a laser front-end sensor mounted on the rear of an AATA bus in service. These "behaviors" were then used to build decision logic to determine when a dangerous situation required mitigation or countermeasures.

General Dynamics then developed a visual warning system. Tests concluded that a light bar with a specific moving light pattern was effective in attracting a distracted driver's attention. This light bar was added to the RICWS and was turned on once a following vehicle committed dangerously aggressive closing behavior toward the rear of the test bus. Three warning algorithms were field tested, each with different parameters defining 'aggressive closing behavior.'

Both Phase II and Phase III of this program produced informative results regarding typical following driver behavior behind buses. The light bar proved effective in modifying following drivers' behavior (with all three algorithms). A set of comprehensive RICWS specifications were generated as well as future commercialization steps for the system.

INTRODUCTION

The RICWS report (which is the basis for this paper) was prepared for the U.S. Department of Transportation, Federal Transit Administration for the development of performance specifications for Rear Impact Collision Warning Systems (RICWS) for transit buses. The actual specifications are not listed in this paper, but may be found in the original report. This research was conducted in this area since one of the most frequent accidents in transit bus operation is when a vehicle collides with a bus from behind: a "rear impact." This type of collision is responsible for significant costs including damage to the bus, injuries to the occupants, and disruption of the operation of the transit agency. In addition, damage to following vehicles (FVs) and injury to their drivers is usually significantly greater than to the bus or its occupants.

In 1994, transit buses were involved in 3,119 rear-end collisions, nationwide. By 1996, that number increased 56 percent. For the same period, the number of injuries increased 161 percent.

Table 1.
Crashes and Injuries for Transit Bus Rear-end Collisions

Year	1994	1995	1996
Crashes	3,119	3,668	4,868
Injuries	1,403	3,262	3,661

Data courtesy of Volpe National Transportation Systems Center, N. Burke, 2/99

Transit buses are particularly susceptible to rear impact collisions because of their frequent stops. Adding to the problem, some bus stops do not allow the bus to pull out of a lane of moving traffic. The DOT Draft Transit IVI Baseline Statistics Study (personal communication, N. Burke, February 2, 1999) indicates that the majority of collisions occur when the bus is decelerating or stopped.

This type accident is common with transit companies all over the country. Nationally, rear-end crashes account for 21.5 percent of all collisions involving buses for 1994 to 1996 (personal communication, N. Burke, February 2, 1999).

According to the 1998 Transit Fact Book, although casualty and liability costs comprise only an average of 2.9 percent of transit companies operating budgets, efforts to reduce the risk exposure, and therefore premiums and claims, by operating fewer miles, having fewer accidents, and/or fewer employees are "often overwhelmed by litigation awards, inflation and state- or region-wide premium increases to cover insurer losses elsewhere." In rear impact crashes, due to the mass of the bus, the resulting collision can be severe for the occupants in the following vehicle, but not necessarily for the bus. Although, there is usually little cost associated with physical damage to the bus, there are costs associated with workman compensation, rider injury, litigation against the following vehicle driver, lost time of bus and driver, and possible drug testing of the driver.

Table 2.
Rear-end Transit Bus Crash Summary

Feature	Most common (%)	Second most common (%)
Number of lanes	Two (41.7%)	More than two (39.1%)
Relation to junction	Non-junction (62.7%)	Approach to intersection (22.2%)
Grade	Level (59.6%)	Grade (15.4%)
Alignment	Straight (89.1%)	Curve (7.6%)
Speed limit	30-45 (55.3%)	50-75 (15.8%)
Following Vehicle speed	<=25 mph (47.3%)	26-40 mph (34.4%) [Largest single 5 mph bin is 31-35, 15.1%)
Lighting	Daylight (85.5%)	Dark but lighted (6.7%)
Weather	Clear (77.3%)	Rain or snow (18.7%)
Bus motion	Stopped (67.2%)	Slowing in lane (13.5%)
Following Vehicle movement prior to critical event	Going straight (82.1%)	Slowing or starting (6.6%)
Corrective action attempted by striking vehicle	None (67.3%)	>2 vehicles involved (15.4%)

From Table 2 it can be seen that this type of collision happens most often with clear weather, daylight, straight road, bus stopped, striking vehicle approaches in same lane at constant 31–35 mph with no corrective action.

Research Approach

The research approach was to divide the effort into three major phases. The first phase was an initial causation study and technology demonstration. Overall the Phase II effort provided a detailed accident profile report, an initial system specification for a RICWS system, and field data collection effort to establish the baseline parameters for a RICWS system. Phase III of this contract provides for outfitting two buses with similar systems which include algorithms and warning lights to study and assess the reactions of following vehicle drivers in response to ignition of the warning light. Phase III also updated the system specifications for a rear impact collision warning system.

The detailed approach in each of the two phases is identified below.

The approach and efforts for Phase II:

- Conduct an assessment of available crash data to characterize rear-end crashes involving buses.
- Completed a warning indicator study to arrive at an "optimal" design of a warning indicator.
- Establish requirements for a baseline data collection.
- Build two testbed Data Collection Systems (DCS) to be used on AATA buses to collect baseline data.
- Generate a "baseline" of on-the-road data to use in assessing the efficacy of the data collection system and to use in building and testing a warning algorithm.
- Build tools with which to analyze the collected baseline data.
- Assess and analyze following vehicle driver behavior as exposed in the baseline data collected.
- Evaluate crash scenarios and possible benefits of the warning system, refine performance specifications, and define evaluation strategies.

The approach and efforts for Phase III:

- Implementation of the code necessary to add the capability to the DCS system to provide ignition of a warning light at appropriate times.
- Algorithm development and validation testing.
- Light bar field testing.
- Replacement of degraded laser IR sensors.

- Human factors testing of drivers approaching the back of a bus under "normal" conditions.
- Collection of data from two buses fitted with the system with warning lights.
- Analysis of collected data.
- Update algorithms to signal the warning light based on field testing.
- Update system specifications.
- Complete the final report and recommendations for next steps.

FINDINGS

Findings in this paper encompass only the Phase II and Phase III efforts. The Phase II findings are identified below and are more comprehensive than the Phase III findings; however the Phase III findings encapsulate the overall results of this program. The Phase II effort is the basic R&D needed to support the Phase III effort. In Phase II, we identified key system parameters and established the plan for the Phase III effort. The Phase III findings are more abbreviated and to the point since they focus on the results of the system performance in an operational environment. Essentially Phase III findings are the "icing on the cake". They are the operational conclusions from RICWS testing in a real environment.

Phase II Findings

Conclusions derived from the Phase II baseline data collection have been developed by manual examination of data from two particular days of collections, the very first (4/25/01) and a day near the end of collections (8/17/01). Algorithms have been run extensively on these two days' data.

Range Sensor Performance did not receive a rigorous or detailed evaluation in a laboratory setting; however a reasonable set of outdoor measurements were made to validate the nominal performance of the sensor. In addition to the outdoor measurements, examination of the baseline data collected helped to characterize the sensor performance. An important note, however, is that the selected sensor for our testbed DCS system may not be the ideal sensor for deployment in transit bus fleets across the nation. In fact, our selection process was driven by a sensor that was a reasonable cost and was commercially available (with no development costs) that would be adequate for this program. As will be identified later in the report, we recommend a different type of sensor for a deployed commercial system. The detailed information provided below is included here since it was instrumental in providing guidance, evaluation and insight into the recommended sensor requirements for a commercialized system suitable for nation-wide deployment. The recommended sensor for commercialization is included in the Phase III findings.

The range sensor's resolution is 15 cm and spec sheet accuracy is listed as + or – 1 percent at 100 meters. Empirical observations of the returns from stationary targets at various ranges tend to support this specification and, in fact, suggest that the absolute accuracy may be better at distances in excess of 25 meters. At closer range this sensor appears to suffer from saturation and possibly cross-talk problems with highly reflective targets, and range measurement accuracy degrades. In fact, the sensor functions quite poorly at distances below 8 meters. In almost any instance, the following vehicle warnings were signaled at distances greater than 15 meters, so the lower range limit was not a significant issue for our testing.

On 4/25/01, the day the bus was put into service, a number of specific range measurements were taken utilizing boards coated with retro-reflective material (see Figure 1). A table of these measurements and the range sensor outputs is shown below (see Table 3).

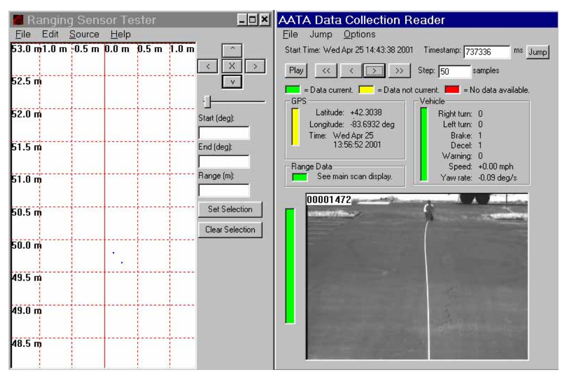

Figure 1. Measuring Range Detection Performance of Range Sensor.

Table 3
Sensor Range Accuracy and Repeatability Observations

Measured Range (meters)	Observed Sensor Range Mean (meters)	Diff. (meters)	Percent Accuracy	Observed Sensor Range Repeatability (meters)
5	2.85	2.15	43	+0.15, –0.3 or more
10	11.4	1.4	14	±0.15
15	14.55	0.45	3	±0.15
20	19.65	0.35	1.75	±0.15
30	29.85	0.15	0.5	±0.15
40	39.75	0.25	0.625	±0.15
50	49.8	0.2	0.4	±0.15
60	59.85	0.15	0.25	±0.30

The table above indicates accuracy in essentially a static environment, and those accuracies are adequate for the calculations needed to calculate when to signal the warning light. However, we found that in the dynamic environment of buses and following vehicles moving, that the specular returns from the following vehicle could jump from one region on following vehicle to another causing an error input to our tracking algorithms. This effect of dynamic jumping of the return from the following vehicle and affecting our tracking algorithms will be addressed in the Phase II findings.

The following factors have been identified and observed in normal operations data that serve to reduce the quality and availability of range returns for objects that are clearly visible in the video record and which, based on their position in the video should have produced a range return. The factors include:

- Intermittent or no returns off some vehicles with no apparent environmental cause (due to vehicle characteristics such as profile, surface materials, angle of presentation).
- Intermittent or no returns off some vehicles due to environmental conditions impairing the range sensor's performance (ambient light energy entering the sensor—such as at low sun angles, rain, fog, smoke/dust, dirt on the sensor face, etc.).
- Intermittent returns off vehicles caused by bus movements (primarily vertical bounce due to bumps or potholes).

Unfortunately, these conditions are difficult to identify automatically, and it is impractical to manually review all the video data to correlate poor range sensor performance with these types of factors (as opposed to the default explanation: no following vehicles present). However, portions of two days of data have been examined manually with the following results (see Table 4).

Table 4.
Manual Assessment of "Interesting Tracks"

Data from 2 hours taken on 8/17/00
(early morning hours – low sun angle)

Manual analysis statistics:	
Sum of duration of tracks	1821705
Number of manual tracks	78
Not trackable	22
Likely not trackable	23
Total probably not trackable	45
% probably not trackable	58%
% likely good tracks	42%

Data from 5 hours taken on 4/25/01
(mid-day hours)

Manual analysis statistics:	
Sum of duration of tracks	7737423
Number of manual tracks	287
Not trackable	19
Likely not trackable	30
Total probably not trackable	49
% probably not trackable	17%
% likely good tracks	83%

Direct low angle sun impinging on the sensor seemed to be the primary environmental factor affecting the sensor's ability to detect returns in the 8/17/01 data (note: table erroneously labels this date as 8/17/00). No other environmental factors (e.g., rain) were observed in these sets of data. Both days examined can be expected to have the same percentage of range return problems due to vehicle profiles. A more "normal" range return behavior is evident in the data from 4/25/01. Making a gross estimate of the percentage of hours with rain and low sun angles (and other effects that similarly compromise optimal sensor performance) as 25 percent, then a weighted average of "percent likely good tracks" as determined by this direct visual examination of the video and range data yields an expected sensor performance of 73 percent. That is, the range sensor produces, on average, good, usable range returns for 73 percent of vehicles that approach the bus on a potential collision course due to environmental conditions.

However, a very significant reduction in probability of detection of an approaching vehicle is not associated with environmental conditions. As indicated above, a number of instances of the system not being able to detect and track a closing vehicle was due to vehicle characteristics such as profile, surface materials, angle of presentation, etc. For example, with an infrared (IR) sensor and eye safe illumination, it is very difficult to get an adequate return from some vehicles, such as a Corvette. This situation is far from limited to Corvettes. Most any small "sleek" vehicle, especially with retractable headlights is not very visible to this type of sensor. Our data analysts estimated that 30 percent of the following vehicles were not identified by the laser sensor. For our field testing this sensor performance issue just removed these types of vehicles from our test set. Though not ideal, we were still able to evaluate algorithms and effectiveness of the light bar over the data set of the vehicles our system could detect and track. However, for a commercially deployed system, it is probably not acceptable to not track 30 percent of the following vehicles, therefore a more robust sensor is needed which can detect almost all vehicles which would be encountered in a transit bus environment.

Ranges to Targets at First Detection were determined by calculations to quantify the desired minimum detection range for approaching vehicles. The following chart (Figure 2) provides guidance on the required distance for first detection of approaching vehicles to allow enough time to flash a warning and expect the vehicle to stop before hitting the bus. The different curves show the results of different braking effort and reaction time assumptions. Common assumptions embedded in these curves are that the detection system has a sampling interval of 0.1 seconds, and that a minimum of five samples are required before signaling of the warning light can occur.

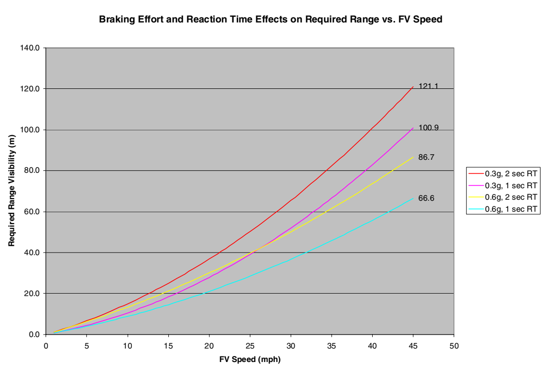

Figure 2. Chart of Required Range of First Detection to Avoid Collision.

The 0.3 G braking curves (labeled as 0.6 G) indicate that first detections must occur between about 45 and 61 meters at 35 mph.

Examination of the collected baseline data for one day's worth (8/17/01) of approaching targets yielded the following distribution (see Figure 3) of first detection distances for a group of 112 vehicle tracks, all of which exceeded (at some point during the track) the following measures of relevance for collision warning purposes (as determined automatically by a tracking algorithm):

- Range rate exceeded 10 m/s closing.
- Time to collision fell below 3 seconds.
- Braking required exceeded 0.25 G.

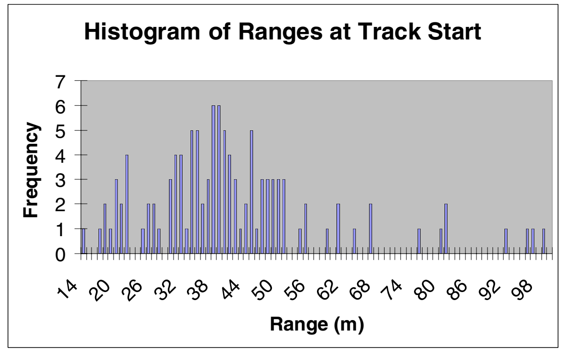

Figure 3. Ranges at Track Start (112 selected tracks).

The mean of this distribution is 41.2 meters, standard deviation 17.1 meters, and median of 38.6 meters.

All approaching tracks for a single day were examined and yielded the following distribution of first detection distances (see Figure 4).

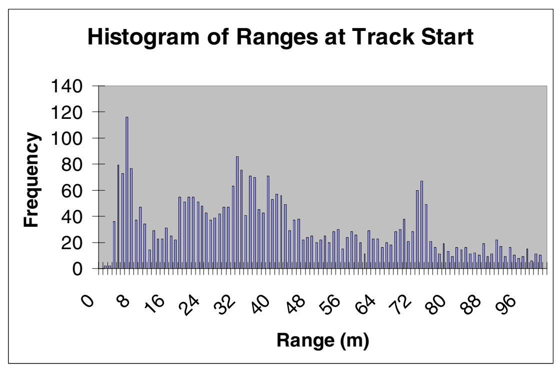

Figure 4. Ranges at Track Start (3255 total approaching tracks, 8/17/01).

The mean of this distribution is 39.3 meters, standard deviation of 25.3 meters, and median of 34.6. The multiple peaks showing in this second histogram deserve further discussion.

The large number of tracks starting within a 10-meter range are due to an observed "spreading" of the range returns from a single vehicle at close range which results in track splitting and spawning within the cloud of range returns (due to the current clustering algorithm utilized to establish the association of range returns to single targets). This origin of the range spreading phenomenon is as yet undetermined, but is likely due to overloading (saturation) of the range sensor detector at close ranges (see Figure 5). Since many of these ranges at track start are due to multiple tracks on the same vehicle, this peak is erroneous.

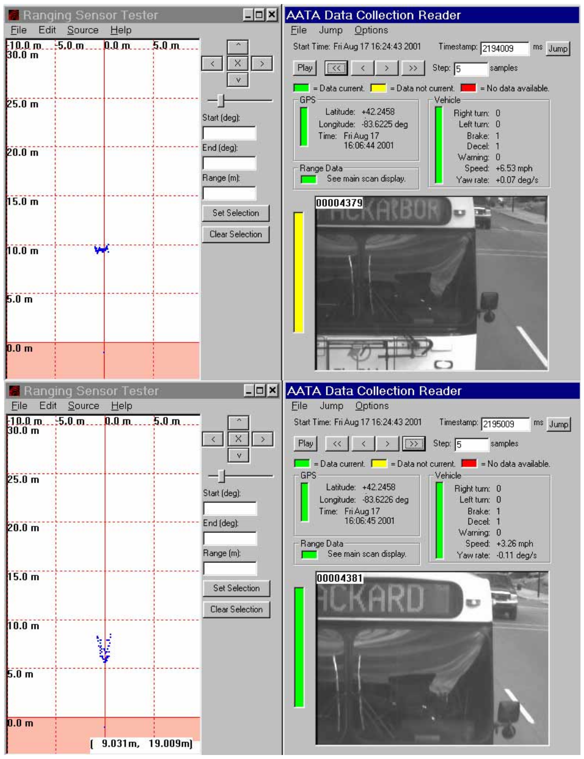

Figure 5. Range Spread Phenomenon at Close Range (within 10 m)
(Note: Lower display is 1 second later than upper display)

The peak at about 76 meters range in Figure 4 indicates that there is a certain class of vehicles that tend to become visible to the range sensor at this range. This class of vehicles includes other buses and large truck tractors – basically anything presenting larger-than-normal perpendicular surfaces to the range sensor.

The remaining middle peak corresponds to the average distance at which the typical following vehicle (a sedan, SUV, or pickup truck) becomes visible. This distance, approximately 40 meters, corresponds to a speed of 32 mph on the 0.6 (0.3) G, 1 second reaction time curve of Figure 2. While not optimal (ideally, ALL following vehicles would become visible to the range sensor at least 66 meters to allow for warning and a complete stop before crash at up to 45 mph) this sensor still provides an adequate range of detection for the majority of vehicles transit buses may encounter in city driving.

In the Derived Parameter Assessment, timing relationships among the data elements are established by construction in the loop sequencing in the data collection system, but detailed timing relationships can vary depending on the instantaneous computational load in the DCS system. These relationships and variations have not been fully quantified, but have been observed in plots to be reasonably accurate. This effect is embodied in selection of a CPU with sufficient power to perform the calculations in the required time.

Analysis of the of the database data (both video and stored parameters) and manual examination of dozens of plots of velocities, accelerations, range-rate, headway time margin, time to collision, and braking required indicate that computations of these parameters are being done correctly.

Crash Scenarios, Performance Specifications, and Evaluation Strategies developed as expected. Based on the extensive manual review of data to date and processing results it would appear that the vast majority of potential rear-end collision incidents occur under the conditions as indicated in our analysis of crash history data—and this is not an unexpected conclusion. Virtually all incidents of "excessive" braking required parameters occur in tracks of following vehicles in the lane of the bus (generally straight and level) that are approaching the bus and ultimately stop behind the bus. The remaining incidents are vehicles approaching in the same lane but which execute a lane change to pass, typically on the left, but sometimes on the right.

Phase III Findings

The Phase III effort was the primary data collection with RICWS systems on two buses over an assortment of AATA routes. This collection was the first test with the warning lights being activated in a field operational environment where drivers would be exposed to the warning system and hopefully modify their driving behavior immediately following the warning light illumination. This Phase III collection was divided into three major sub-collections, each one utilizing a different collision warning criteria; 0.3 G fixed threshold, 0.225 G fixed threshold, and the CAMP algorithm. Though this program was not funded to do a major evaluation or optimization of warning algorithms in Phase III, we elected to evaluate three different criteria in an effort to better characterize the motorists reaction to the system and either select the best approach or at least establish a trend. The original plan was to analyze the Phase II data collection data where baseline driving behavior was collected. However in this scenario, though excellent baseline data was collected, it of course did not include driver's response to the warning because the lights were not illuminated. Our original plan was to develop the algorithm from this baseline data with no need to implement secondary modifications or conduct multiple algorithm studies during the Phase III collection where motorist response to the warning was included. However, with the questions initiated by the combination of the initial 0.225 G threshold results, the results of our human factors testing, and the importance of the CAMP algorithm and the respect for that research, it was deemed most appropriate to evaluate multiple scenarios in the operational field test. The downside of this approach was that for any given warning algorithm there would not be a sufficient number of incidents to statistically prove it was effective in mitigating risky driving behavior behind transit buses. If we would have gone down the path of selecting and utilizing only one algorithm, then we would have had the potential to prove that that one algorithm was or was not effective in this transit bus scenario, however we would not have developed the understanding of how effective that algorithm was with respect to other potential algorithms. It would just be a single point analysis.

<u>The Warning Light Design and Effectiveness Evaluation</u> was one of the key challenges of this program. General Dynamics was to design, build, and evaluate the warning lights that were to be mounted on the back of the bus. These warning lights are the interface from the RICWS to the following vehicle driver. The goal for the light bar is to capture the following vehicle driver's attention and elicit a response as quickly as possible.

The Vision Detection Laboratory at the University of California, Berkeley, led by Professor Theodore E. Cohn, provided the necessary design, build, and human factors testing to evaluate and select the system that provided the highest performance. The result of their warning light research is shown in Figure 6. The light bar is mounted horizontally on the back of the bus. It is an LED 8-segment light bar system (50 inches long by 4 inches high), where the segments are grouped in pairs. Each pair, starting from the middle pair and working outwards to the left and right sides of the bus, are illuminated. These sequence pairs are a symmetric set of segments centered about the centerline. So the middle two segments are a pair. The next adjacent segments are a pair, and so on. As can be seen in Figure 6, the segments are amber, and the intensity was set to the same light intensity as a brake light.

The human factors performed at the Vision Detection Laboratory indicated this configuration to elicit the fastest response from the test subjects.

Figure 6. Warning Light Bar on AATA Bus.

<u>Following Vehicle Driver Behavior</u> was recorded without any public education being provided. Two buses at AATA were equipped with the RICWS. So all following vehicle drivers who encountered warnings from the yellow warning light bar reacted totally on intuition and basic understanding as to what the flashing yellow warning lights were trying to tell them. In the future, if RICWS systems are widely deployed, it can be conjectured that the driving public will have been educated somewhat to the intention and goals of RICWS systems, and as such might react even more favorably.

The video recording of the data acquisition system was critical in evaluating driving behavior. Our analyst soon discovered that as soon as most drivers see the bus in front of them they start making plans to get out from behind it. Whether their actions are to immediately pull into an open adjacent lane, or start to jockey for position to pull into an adjacent lane opening, or even to force an opening in the adjacent lane, their goal is predominantly to get out from behind the bus. And one of the very common maneuvers is to jockey for an open position in the adjacent lane while approaching the back of the bus on a collision course. They pull into the adjacent lane at the last second, all totally planned and fully aware of the situation. In this scenario, the following vehicle driver probably does not need to be warned about the impending collision with the bus, because in most instances he seems to be fully cognizant of the closing velocities and the opportunity he is generating to swerve around the bus.

Our RICWS system, unfortunately, is not robust enough at processing the collected data to understand the driver's plans. The RICWS can only look at closing velocity and lateral velocity (and of course position with respect to the bus). From our video analysis we identified that there is not some typical following vehicle velocity behavior that is a high predictor of what the intentions of following vehicle driver is planning on doing. So the best a RICWS system can do is signal its warning when the closing velocity and distance of the following vehicle's "Braking Required" exceed the algorithms threshold in a driving scenario where there are no lateral velocity changes to indicate an impending lane change.

For this common swerve scenario, all a RICWS system can do is activate its warning lights. However, there may be a dilemma here: if the warning lights are activated, how will the driver react in the midst of his planned risky behavior? Additional human factors research is needed to validate that drivers would not react adversely to a rear impact collision warning in this situation.

Determining Effectiveness of the RICWS in Transit Bus Field Operations requires several evaluation parameters. Various choices exist for definition of the specific warning criteria for signaling of the warning light. Making this choice is a complicated process that involves simultaneous balancing of trade-offs having to do with:

- Sensor capabilities and characteristics:
  - Lateral distance/velocity accuracy, resolution and dynamic range.
  - Longitudinal distance/velocity accuracy, resolution and dynamic range.
  - Contrast ratio between targets (following vehicles) and background clutter.
- Striking a balance between false alarms and missed threats.
- Timing of warning with respect to need (early enough to prevent crash, but not too early so as to represent a nuisance alert).

We have looked at using three possible scenarios for driving the warning indicator:

- An alert based on simple braking required threshold of 0.3 Gs.
- An alert based on simple braking required threshold of 0.225 Gs.
- The CAMP forward collision warning alert equation.

For the fixed threshold approach, we collected data and provide warnings at both the 0.3 G and 0.225 G thresholds. We also collected data utilizing the CAMP algorithms.

In the overall analysis of the performance of the three thresholds, we primarily compare two data plots. The first graph is a plot of the braking required history for all incidents where the following vehicle exceeded the threshold and the warning light was signaled. The second comparison graph is the plot of the braking required histories for all following vehicle pseudo-incidences. These pseudo-incidences are situations where the following vehicle met all requirements to signal the warning (both threshold and parameters), however the warning was not signaled because it was not enabled. Pseudo-incidences are very intentional, they occur in time periods when the system is fully operational except for the final signaling of the warning light. Their purpose is to provide the reference or ground truth for the field operational test.

The key comparison that is made between the incidents and the pseudo-incidents is comparison of peak values of braking required. For following vehicle incidences where the light is signaled, if the system is effective, the driver will respond to the RICWS warning light and slow down. In the following vehicle pseudo-incidences, the warning is inhibited from being signaled, and it is expected that the drivers would continue to drive at the bus for a time period, and as such their path histories would have higher braking required. In fact, it is this single parameter comparison that we use as the metric for evaluation of the effectiveness of the system.

As any of the charts below are analyzed, it should be noted that only two seconds of data was plotted before the threshold warning point. In many cases data preceded this point, but was truncated for convenience of plotting. After the threshold warning point, not all data returns to 0 Gs braking required, which seems a little odd at first glance, but the selected IR laser sensor does not reliably work below 8 meters distance behind the bus, so data is truncated at this point. In all cases, there were no collisions into the back of the bus, so all vehicles did stop behind the bus, pulled out of the threat zone behind the bus, or the bus started pulling away after the following vehicle entered the 8-meter zone.

Another aspect of the plots for each of the data sets is the number of traces on each graph. For the two fixed threshold sets (0.3 G and 0.225 G), there are few more traces (braking required incidents) for the non light activation scenario than on the activation scenario. In both cases, the data analyzed was based on a 50 percent duty cycle between activation and non activation, so the different number in the plots was just a matter of statistics. However, for the CAMP algorithm, there were 13 CAMP warnings with the light activated, and 183 without. This apparent discrepancy is due to processing a much larger set of data where the light was not activated. Any of the data which was collected where the light was not activated is potential data for reprocessing to evaluate any algorithm. We took advantage of this for the CAMP evaluation. Even though the CAMP light activation data was collected in September, the data set for CAMP with no light activation was a time period over March and April.

The 0.3 G Fixed Threshold Data Collection is the least conservative warning criteria used in our data collection. From an intuitive standpoint, this is the value of braking required which most people in our human factors testing felt was the maximum braking required level that could be done while still feeling "comfortable". It should be noted that the evaluations were done by the subjects deliberately driving towards the back of the bus and braking at the last instance where they felt comfortable. As mentioned elsewhere in this report, at 0.3 Gs, items start sliding off of seats (if they are not restrained).

The first plot which is shown in Figure 7 is the plot of the braking required histories with the warning light enabled at 0.3 Gs. There are two major observations. First, there were only two such incidences while the light bar was enabled. And second, and most important for our analysis, the peak braking required was only 0.306 Gs, just slightly higher than the 0.3 G threshold for signaling the warning. It also should be pointed out that this peak occurred within tenths of a second after the warning light came on, almost too fast for a driver to react, unless he had his foot on the brake and was starting to stop anyway.

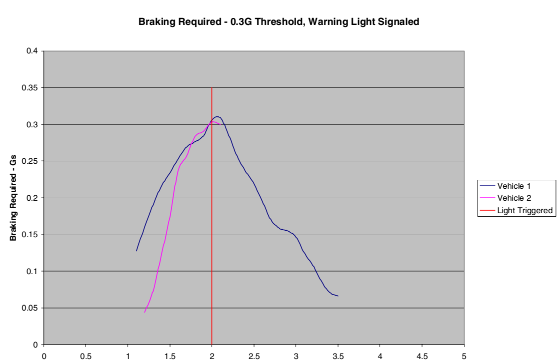

Figure 7. Braking Required, 0.3 G Threshold, Warning Signaled.

The Figure 8 is the second plot of the pair of analysis plots. It is the plot of the pseudo-incidences for the following vehicle. In this case, even though the data was collected, the warning signal was not activated. As shown in the plot, after the warning light should have been activated, the motorists kept proceeding towards the bus and the braking required values continued to increase to average peak value of 0.33123 Gs. Comparing the average peak braking required of these two plots, it can be conjectured that the RIWCS system was effective (7.62 percent reduction in braking required) in getting the drivers' attention and they responded positively and slowed down.

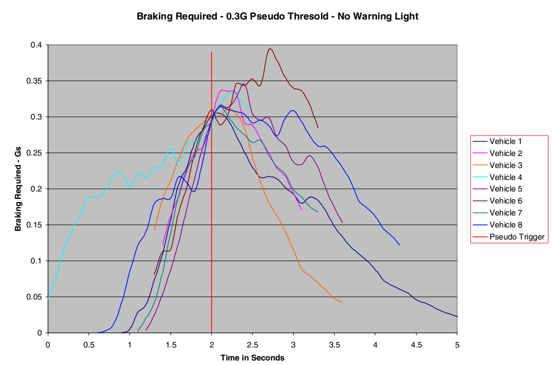

Figure 8. Braking Required, 0.3 G Threshold, Warning NOT Signaled.

The comparison of these two plots shows a trend, but does not prove the results statistically. In addition, considering how few plots are generated, it can be conjectured that different warning threshold might be appropriate that would warn more drivers more of the time.

Related to potentially picking a more conservative warning, analysis from the human factors perspective may shed some light on the issue. In our human factors testing, if the driver was aware of (looking at) the bus while approaching, 90 percent of our drivers felt comfortable with this 0.3 G braking required regime. If a driver were not paying attention (not a condition evaluated in our human factors testing) and it took our RICWS warning to get their attention, then the CAMP research indicated that it would take the driver approximately 1.38 seconds to respond, which would subtract from the time to impact, which in turn would require a higher braking required value. At 30 mph, this new braking required value is 0.422 Gs due to time lost during driver response, assuming the driver immediately sees the RICWS warning lights. As shown in our human factors testing, none of our test drivers felt "comfortable" braking at this level; therefore the team concluded a more conservative approach was needed to warn the driver earlier.

Two approaches for this were evaluated. The first is a lower fixed threshold, and the second is the CAMP algorithm that takes into account time delay and modulates effective braking with closing velocity.

Despite the decision of the research team to look at more conservative approaches, the comparison of braking required with and without activating the warning light utilizing an algorithm with a fixed threshold of 0.3 Gs indicates that the RICWS was effective in modifying the following vehicle's driver behavior by lowering the braking required by 7.62 percent (for this data set) when the light was activated.

<u>The 0.225 G Fixed Threshold Data Collection</u> is the next more conservative warning criteria we implemented. The first of the two graphs (Figure 9) shows the time histories of the following vehicle incidents where the warning threshold was triggered at 0.225 Gs.

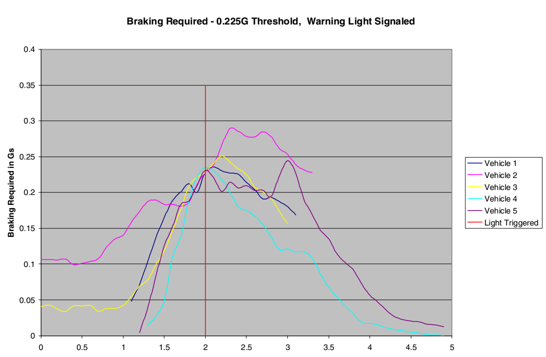

Figure 9. Braking Required, 0.225 G Threshold, Warning Light Signaled.

As can be seen in Figure 9, we had five incidents where the warning was signaled and the drivers responded. The average peak braking required value for this set of following vehicle incidents is 0.2496 Gs. The comparison set is in Figure 10, where we had 36 incidents (note the legend only had enough space to display Vehicles 1 through Vehicle 31, but there are actually 36 traces) where the light bar would have been signaled if it was enabled. The average peak braking required value for this set was 0.2723 Gs. This showed a reduced braking required of 8.3 percent.

Therefore, the comparison of braking required with and without activating the warning light utilizing an algorithm with a fixed threshold of 0.225 Gs indicates that the RICWS was effective in modifying the following vehicle's driver behavior by lowering the braking required by 8.34 percent (for this data set) when the light was activated.

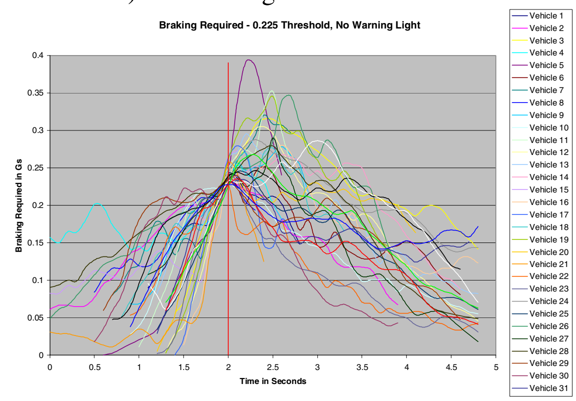

Figure 10. Braking Required 0.225 G Threshold, No Light.

<u>The CAMP Warning Algorithm Data Collection</u> takes into account a 1.38 second driver response time and the braking required threshold is modulated by the speed of the following vehicle closing rate. At higher speeds, the braking required threshold is increased. For example at a closing velocity of 15 mph, the braking required threshold utilized is 0.309 Gs (this does not include the 1.38 second time delay), and at 60 mph, the braking required threshold is 0.455 Gs. And of course, these values are effectively modified by the inclusion of the 1.38 seconds delay time.

The utilization of the CAMP algorithm to signal the warning light is presented in Figure 11. The vertical line at the two second point is the point when the warning light was activated. As can be seen comparing Figure 11 and Figure 9, the CAMP approach is more conservative than the 0.225 G fixed threshold. In fact, some of the following vehicle braking required histories are incredibly conservative (see vehicle 10 and vehicle 12 traces in Figure 11) where the CAMP threshold is down to almost 0.1 G. At this type of level (almost coasting to a stop) we would expect many drivers to consider this a false positive. Upon examining the velocity data, range data, and video associated with these braking required histories, it became apparent that these cars were going slow at short range and were just following the bus. However, their mild driving behavior at this short range triggered the CAMP algorithm. We cannot automatically jump to the conclusion that these following scenarios should be considered false positives, since in the real driving world; there are many low speed short range collisions in stop-and-go traffic. However, intuition tells us that there are many more situations where a less than 5 mph activation of the warning light would be considered a false positive by the following vehicle driver, especially if the driver is just following the bus slowly, and not in a major slowing down mode. By studying the tracks histories of the following vehicle, and looking at the change in braking required, the closing velocities and the distance to the bus, etc., we believe the low speed warning could be significantly improved by appropriate examination of the available data by an enhanced algorithm. Therefore we recommend that this low speed area needs more research. It may also drive the sensor parameters specifications to work at a shorter range.

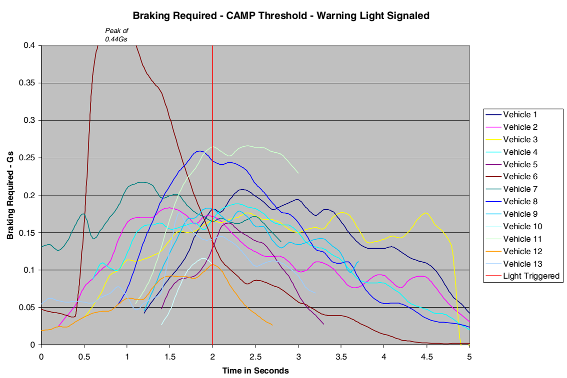

Figure 11. Braking Required CAMP Warning.

The comparison plots for the CAMP algorithm, with and without the warning lights are shown in Figure 11 and Figure 12. The comparison shows that there are many more vehicle braking required histories without the light activation. The data for the CAMP braking required with light activation was collected during September, and unfortunately one of the AATA buses was out of commission for garage work, so we only had a small set of data to base our results on. The reference set in Figure 12 without the warning light activation was from a much larger set of data during March and April. As such we had 183 pseudo warning incidents without the warning light and only 12 incidents with the warning light.

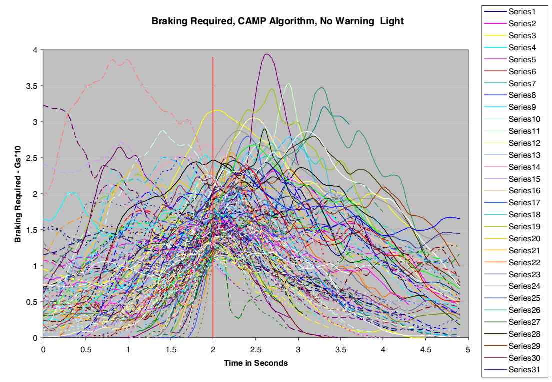

Figure 12. CAMP Braking Required – No Light Activation.

In as mentioned above, there are many very low speed (less than 5 mph) incidents that are potentially false positives in both figures. As such, to improve the quality of the analysis, we manually went through the data sets and eliminated the tracks at less than 5 mph. The results of this culling of the slow speed incidents where there was not an appreciable rate of change of braking required (following vehicle not stopping aggressively) are shown in Figure 13. As can be seen in Figure 13, vehicle traces 6, 10, and 12 have been eliminated. Also, vehicle 6 was slowing down significantly from 0.44 Gs braking required down to 0.138 Gs braking required at the warning point, which probably means the following vehicle driver was well aware of the bus before the warning, and the warning was a false positive. So this culling significantly affected the statistics of this small set.

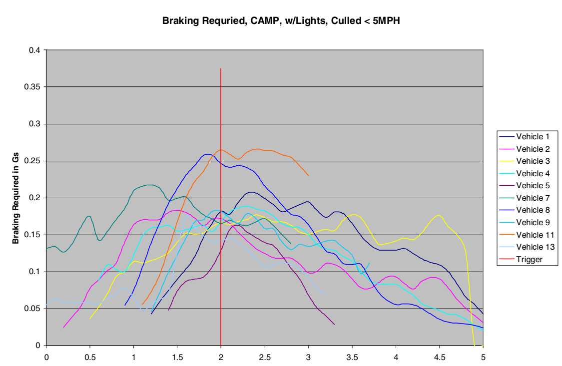

Figure 13. CAMP Braking Required, w/Lights, Culled < 5 mph.

In the same vein we have eliminated the less than 5 mph vehicle histories from the data set in Figur where the light was not activated. This reference set is shown in Figure 14. This culling out the less than 5 mph incidents reduced the number of pseudo-incidents from 183 down to 134. As a side note, if we would have culled out the incidents where the speed was less than 10 mph, the number of incidents would have been reduced to 74. For our analysis of the CAMP algorithm, we will use the data sets in Figure 13 and Figure 14. As in the fixed warning thresholds, we looked at the average peak braking required, however in the CAMP plots, we will specifically only will look at peaks that occur after the warning has been signaled. It does not make sense to look at peaks before the warning, since the warning light could not have influenced the driver's behavior before it was activated. For the fixed threshold algorithms we did not need to worry about this effect, since in the worst case situation, the trigger point would be the peak value.

For the data set where the CAMP algorithm triggered the warning lights, the average peak braking required that occurred after the warning was activated was 0.1917 Gs. In the reference data set where we did potentially modify the driving behavior (and hence the data) with activating the light, the average of the peak braking required that occurred after the warning would have been signaled was 0.1968 Gs, only 2.6 percent higher than the where the light was activated to encourage the following vehicle to slow down. Though this does show the trend, the margin of difference is small. One of the issues that might be related to this is the fact that the set with no light is reasonably statistically significant, and the set with the light activation is not.

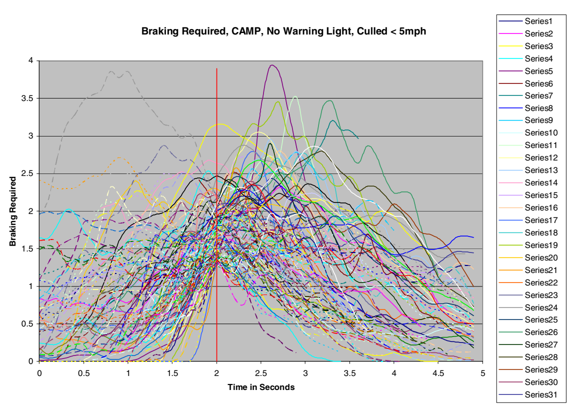

Figure 14. CAMP Braking Required, No Warning Light, Culled < 5mph.

And maybe even more importantly, with the CAMP algorithm the braking required value for triggering the light is modulated by the following vehicle's closing velocity. So, since we do not have a statistically significant set of data for the CAMP algorithm where the light was activated, it would be nice to have a metric that eliminated this variation. From analysis of the data, it was determined that such a potential metric was the "average difference between the peak braking required (after the warning light activation) and the braking required at the CAMP warning threshold." Intuitively this makes sense. This metric looks at how much higher the braking required value went after the light was activated. If in general this delta value is higher with no warning light, then we can conclude the drive reacted and slowed down sooner. For our two data sets, this delta peak value for the set with the warning light was 0.0102 Gs and the delta peak value for the CAMP set without the warning light was 0.0302 Gs, or almost 3 times higher. These acceleration values are not large values in themselves, but they do support the trend that shows the lights do cause the following vehicle drivers to modify their behavior to a more conservative regime. And we should not just discount this trend just because it is based on a small number. For example, at a 0.25 G threshold braking required value, there is one incident every 19 hours. At a threshold that is 0.05 Gs higher 0.3 Gs, an incident occurs approximately every 83 hours. So even though these are small numbers, when considered as differences, they can represent a significant difference in a driving trend.

CONCLUSIONS AND RECOMMENDATIONS

The result of this research lays much of the foundation for implementing/commercialization of RICWS for transit buses, however there is more work to be done. This proof of concept effort has developed a working testbed system that has been installed on two Ann Arbor Transportation Authority (AATA) buses and run in their normal operations. Results of the testing have shown the trend of the RICWS system causing the following vehicle drivers to modify their driving behavior to be more conservative. The following drivers stop sooner with less braking required, which is a less risky driving behavior.

This research paves the way to establish standards and/or potential regulations for RICWS systems. A standard that identifies requirements should encompass the light bar warning system and the algorithm for activating the warning to provide a consistent warning environment to the driving public. The remainder of the RICWS specifications should be specified as a recommended practice (such as an SAE recommended practice). Any particular implementation with a given sensor may require tradeoffs between the specifications. As a recommended practice, the manufacture is allowed to perform engineering tradeoffs for their particular sensor selection. If it were an absolute requirement or regulation down to the level identified in the final specifications, then there would be almost no latitude for switching sensors. For example, a millimeter wave radar sensor might not be able to track lateral velocity as accurately at the laser sensor, however the target (following vehicle) cross section (reflectivity) might be better behaved for millimeter wave, and therefore the overall lateral performance of a millimeter wave system could be better. So it is important to separate and apply absolute requirements and recommended practices appropriately.

The RICWS system as demonstrated in our field testing successfully caused the following vehicle driver to modify his driving behavior behind transit buses in a positive manner. Though more confirmation is needed, such a concept could easily be considered for other vehicle segments. There is no reason to believe applying such a system to other vehicle segments would not mitigate those rear-end collisions. A RICWS system should be able to be applied to trucks which also suffer from a relatively high rate of rear end collisions. And in the largest segment, passenger cars, again rear impacts are a significant issue and such a system might provide significant mitigation. If other segments are addressed, from a public education perspective and the desire to elicit a similar positive response from following vehicle drivers, similar warning devices should be considered for all vehicles. Applying RICWS to these multiple vehicle segments will entail a compromise for packaging of the warning light system. Of all the vehicle segments, the transit bus is probably the easiest to package our rather large warning system evaluated in this report. However, if RICWS systems are to be considered for other vehicle segments, the salient features of the warning lights (color, brightness, pattern, rate, etc.) should be same for all vehicle segments. Packaging will be one of the key issues, and as such light size, mounting location, across the various segments will need to be tailored to the configuration of vehicles in each segment. The ultimate goal in the multi-vehicle segment would be for the driving public to recognize that sequence pairs of amber light blinking outwards means that the motorist is approaching the leading vehicle too fast and corrective action is needed.

There is significant potential for improving the safety for the driving public with RICWS systems, and the technology is well within the grasp of the industry. There are no new technology breakthroughs that are required for commercialization, and the basic concept is sound. We have demonstrated the following positive aspects from this program to support commercialization of RICWS:

- That a relatively low cost IR Laser sensor was accurate enough to provide the range and angle data necessary to demonstrate the functionality of RICWS (for the vehicles that the sensor could see).
- A medium scale on-board microprocessor (333MHz Pentium II) was adequate to perform the calculations necessary to track incoming vehicles and perform the warning calculations. No optimization was made for computational efficiency.
- That the light bar warning design was effective in conveying the state of warning to the following vehicle drivers.
- The RICWS proof-of-concept system was effective at causing the following vehicle drivers to modify their driving behavior a positive manner.

This program has also identified the following near term areas that need to be addressed before the final steps of commercialization can be undertaken:

- A more robust sensor needs to be demonstrated and evaluated. The sensor needs to be able to acquire and track almost all vehicles on the road that could be in a position to follow transit buses.
- Establishment of an accepted protection range behind transit buses.
- Determination of how to handle following vehicles swerving around buses.
- Enhancement of the qualifying parameters of when to activate the warning system.
- Enhancement of the CAMP algorithm for low speed operations directly behind the bus to eliminate nuisance warnings.
- Enhancement of the CAMP algorithm for near-range operation behind the bus to eliminate nuisance warnings.
- A larger Field Operational Test (FOT) to characterize crash mitigation performance of RICWS systems applied to transit bus fleets.
- Financial and return on investment (ROI) analysis of RICWS. This would involve working with a potential RICWS manufacturer to estimate system prices for range of manufacturing volumes. The product cost of RICWS systems should be less than the cost of forward collision warning systems due to many reduced requirements. The RICWS does not need to integrate other systems to estimate roadway geometry, the vehicle velocities should be lower, and the RICWS has a less severe task in assessing

targets with collision potential (it does not have to worry about separating out stationary targets within and outside of the vehicles pathway). The ROI analysis would take into account system costs, installation and operations costs, accident costs, insurance aspects (if applicable) and the probability of the RICWS mitigating rear-end collisions.

- Present the salient features of RICWS and ROI analysis to transit bus fleet operators.

Though the list of next steps is longer than the accomplishments list, the concept and the fundamentals of the technology have been demonstrated. There are no major technological hurdles to overcome in the next steps, however there is engineering and sensor work listed above which must be completed to support deployment of a robust RICWS product.

SUGGESTED RESEARCH AND NEXT STEPS

There a few areas or issues that were not fully resolved that should be resolved before RICWS systems are commercialized. This section will identify on them. The following research steps are not in any order of priority.

Protection Range – Following Vehicle Speeds

The maximum operating range of a RICWS system is dependent on the maximum speed of the following vehicle that is desired to protect from. For instance, at 60 mph utilizing the CAMP warning criteria, the following vehicle needs to be warned at 118 meters. At 35 mph the safe warning distance is only 55 meters. This may be a regulatory issue, however; it is recommended that a study be performed to establish a statistical distribution of driving speeds over transit bus routes across the nation. From this distribution, a recommendation can be derived as to the maximum speed and associated range for a following vehicle that the system must protect from. We feel the industry needs a well-founded agreed upon value for range of operation.

Determination of How to Handle Swerves

As identified in this report, following vehicle swerves around the bus are a very common occurrence, in fact it is much more common an incident than where the following vehicle comes to a stop behind the bus. Many of these swerving following vehicles wait to the last minute to swerve, so the RICWS sees a driving scenario which is defined as an incident and will trigger the warning system to alert the following driver, but the following drive is well aware of the bus and in fact is concentrating on getting around it. However there is an unanswered question as to how the swerving motorist will react to the warning lights being signaled as the swerve is being initiated. A human factors study needs to be performed, with the desired goal to show there is no deleterious affect. If it is a problem, then more research is needed into a much more robust approach to identifying a planned swerve.

Millimeter Wave Sensor

Some of our previous conclusions identified that an IR sensor is not the ideal sensor for a RICWS system, and it was conjectured that a millimeter-wave radar sensor would perform better. A system demonstration utilizing a millimeter-wave radar sensor instead of the IR sensor is needed. If the demonstration is successful, then in analyzing the RICWS data, it is expected that many fewer incidents would be considered false positives due to the tracking of well behaved reflections from following vehicles.

Parameters for Qualifying Potential Incidents

Two major events must occur before the warning light is signaled. First, the following vehicle must exhibit a certain behavior before the warning system is enabled. The second event that must occur is that the following vehicle must exhibit a closing velocity and distance that triggers the CAMP algorithm. We believe the CAMP algorithm is reasonably adequate (see Section 4.2.7); however we believe the parameters that characterize the following vehicle driving behavior need improvement. Presently the parameters include such criteria as: 1.) the following vehicle must have been in the alert zone behind the bus during some time in its trajectory history, 2.) the vehicle must have crossed the centerline of the alert zone, 3.) at the time to activate the warning, the following vehicle must be within + or – 2 meter corridor of the center line of the bus, etc. These parameters and approach need at least a second pass on their development to improve the robustness of the performance of the system. The upgraded parameters should be tested in a field operational environment.

Statistically Prove Performance

One of the major short comings of this program is we did not successfully prove (statistically) that a RICWS was effective. We showed trends that made sense, but did not collect enough data on any particular configuration statistically prove effectiveness. In hindsight, a better characterization of this effort is that it was an extensive proof-of-concept program. Therefore, it is recommended that after some or all the improvements to the system (as recommended in this section) are made, that another field operational test be conducted to prove the effectiveness of a RICWS in operations.

Data Mining of Evaluation Data

Our analysis focused on braking required as the key metric for evaluating the performance of the system. The database of at least 200 gigabytes of data is a rich resource of information that has not been fully tapped. In addition to the key evaluations we performed, other studies could be performed that would help understand the drivers behavior, understand more about the required RICWS performance specifications, and more about the effect of the warning system. For example, analysis could be performed on the time averages of following vehicle path histories, evaluation of stopping distances from the bus, detailed analysis of lateral position and velocities of following vehicles both with and without the activating the warning lights (may provide insight into following vehicle swerves), regression analysis of following vehicle behavior with initial velocity of the following vehicle, and regression studies of following vehicle maneuvers with respect to the position the bus is with respect to the normal lane traffic. The database is a rich source of information that when analyzed will probably provide greater insight to driving behavior.

Near-Range CAMP Algorithm Performance

The CAMP algorithm seemed to provide the most reasonable approach as to when to warn the following vehicle driver. It takes into consideration the delay time of the driver response and it compensated for drivers wanting a less conservative warning at higher speeds. One of the trends we noticed in the analysis of the data with the warning light activated was that most drivers reacted much more quickly than the expected 1.38 seconds identified in the CAMP algorithm. It is postulated that driver typically were already planning to stop and had their foot on the brake, and when our warning light was activated, almost immediately pressed on the brake pedal initiating braking quicker than expected. More study to confirm this trend would benefit the decision analysis needed to help decide what a false positive is and what is not. After the algorithm is enhanced, some roadside surveys of drivers or a public web site to acquire following vehicle driver feedback for such situations maybe helpful in understanding the driving public's reaction to the light system.

CAMP Algorithm Performance at Low Speed and Short Range

The CAMP algorithm performed as expected in most situations. However, at short range and low speed in both data sets (with and without light activation), there were many identified incidents where the CAMP algorithm activated the warning signal with the braking required and following speed at very low levels. Of the 184 identified CAMP incidents, 49 incidents (almost 27 percent) were at 0.126 Gs or less, with associated closing velocity less than 5 mph. In viewing the video for many such incidents, it was readily apparent that the drivers were following the bus at a slow speed, and were very much aware of the bus in front of them when the CAMP algorithm indicates the warning lights should be activated. These situations have a very low braking required associated with them, under 0.126 Gs. This is a short coming of the CAMP algorithm as applied to RICWS systems. Development to improve slow speed following warning is very much needed. This region of performance is a little suspect, and potentially could be considered a false positive. A more in-depth study is desired to confirm the performance of the CAMP algorithm at low speed and short range. If the study indicated that for a RICWS application on transit buses that the CAMP algorithm was too conservative (tending towards false positive), another parameter in the CAMP equation could be added to compensate for these scenarios.

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