Side Collision Warning System (SCWS) Performance Specifications For a Transit Bus May 2, 2002

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Side Collision Warning System (SCWS) Performance Specifications

I. Background

This performance specification has been written based on two and one half years of work with the Federal Transit Administration, the Pennsylvania Department of Transportation, the Port Authority Transit Agency of Allegheny County and research conducted by Carnegie Mellon University. This document has a brief introduction to the project, followed by the performance specifications and explanatory text, and concluding with appendices to clarify and illustrate various aspects of the specifications. The full scope of the research project is summarized in the report "Development and Testing of Performance Specifications for a Next Generation Side Collision Warning System", and the various scholarly publications and official reports listed in that report's bibliography.

Performance specifications for Side Collision Warning Systems for transit buses define what data must be collected, the accuracy of the data, the functions of the algorithms, and the necessary outputs of the system in terms of signals, reliability, consistency and robustness.

A. *History of Side Collision Project*

The work started by conducting accident analysis on data collected from National Transportation Statistics, Fatality Analysis Reporting System (FARS), and the General Estimates System (GES), State of Washington, and local data to determine the conditions reflected in side collisions. Secondly, existing systems for trucking applications were assessed to see their applicability to the transit industry. They were deemed not applicable. The types of accidents for which the trucking systems have been designed are mostly lane change-merge accidents on the open road, where the truck strikes another vehicle that may be in the driver's blind spot. It is worth noting that the classic lane change/merge accident, for which commercial truck sensors are designed, accounts for only about 6% of the total number of bus accidents, and none of the fatalities in our sample.

SCWS are also commercially available for cars. Because most car owners are not willing to pay a lot of money for SCWS and the blind spot of cars is much smaller than the blind spot of trucks, SCWS for cars usually have infrared proximity or sonar sensors which cover only the few square meters of the blind spot.

The kinds of accidents encountered by transit buses are much different: the objects struck are likely to be smaller (including pedestrians, stationary objects such as lampposts, and cyclists); the normal operating environment is much more cluttered; and the boundary between a safe and a dangerous situation is much more difficult to discriminate.

In the summer of 1998, we did a small precursor study, separately funded, to understand the applicability of these technologies in a transit context. We installed both rear-looking and commercial side-looking CWS on a PAT transit bus. As a demonstration, the systems were very successful. The rear-looking system illustrated the potential for detecting cars approaching from the rear; it was connected to a variable message sign on the back of the bus warning the driver to “slow down!”, followed by an air horn for truly inattentive drivers. The side-looking system used four sonars along the side of the bus to detect pedestrians and to warn the driver.

The demonstration was successful; however when PAT put the demo bus into service with the side warning system enabled, several flaws became rapidly apparent. First, the sonar would miss important objects. The demo set-up had only four sensors spaced along the side of a 40-foot bus. This is adequate for a truck application, looking for a car in the adjacent lane, since cars are typically at least 15 feet long and therefore could not get lost in between sensors. But for the bus application, the targets of interest include much narrower objects, such as pedestrians, lampposts, mailboxes, signs, trees, etc.

More significantly, the interface as configured generated an extremely high number of nuisance alarms. For the truck application, the sensors are configured to cover a lane width, approximately 4 meters. Any object within that range would cause the light in the mirror to illuminate, or, if the turn signal were on, the audible tone to go off. Buses usually operate in the curb lane of urban streets, and are therefore very often within 4 meters of mail boxes, traffic signals, pedestrians, parking meters, and parked cars. When picking up or dropping off passengers the bus sometimes even touches the curb and people and objects can be only a foot or so away from the bus. There is a tremendous amount of “clutter”, people as well as objects, which can be found very close to the bus.

B. *Clearly, the commercial systems designed for trucks and cars cannot be simply adapted for transit buses. It was necessary to study in detail all the factors contributing to bus collisions and find ways to have a SCWS which effectively identifies dangerous situations without causing too many nuisance alarms.Reducing Nuisance alarms by Probabilistic Reasoning*

In order to separate safe from unsafe situations, it is necessary to model the future trajectory of the bus and of objects. In some cases, this is straightforward geometry: if we know the current motion of the bus and the current motion of an object, we can project into the future and see if their courses intersect. In other cases, however, this requires interpreting the scene and reasoning about changing trajectories. An object identified as a lamppost will remain fixed; a car can move, but has limits in turning radius and acceleration, which bound its likely future positions; a pedestrian can be less predictable. For instance, a pedestrian walking on a sidewalk is likely to stay on the sidewalk; they may step off the curb, but with lower probability. The bus itself may accelerate or turn; cues to its future actions come from monitoring measurements such as steering wheel position or cues such as driver actuation of turn signals. Since the margin of safety for a bus is small, we cannot assume the worst case actions of the bus and of surrounding objects, or we will be overwhelmed by nuisance alarms. Instead, the SCWS needs to reason probabilistically about likely future positions, and about the probabilities of collisions. Also, the SCWS cannot have a single threshold for collision / no collision; instead, it will have to have a graduated response, with multiple “safety levels” corresponding to increasing degree of threat.

In summary, at the highest level, an SCWS for the transit environment requires:

- Sensing and predicting bus motion. Cues to the bus's future trajectory come not only from the steering wheel and current velocity, but also from the turn signal, door open or closed; from environmental cues such as the location of curbs; and even potentially from knowing the bus's current location along its route
- Sensing and predicting object motion. The current location and motion of an object in the environment is the first important cue; but should be supplemented with other cues (is this a car? A lamppost? A pedestrian? Is it in the roadway or on the sidewalk?).
- Assessing the likelihood of a future collision. Once the bus and surrounding objects have been sensed and modeled, software needs to assess the chance of a collision with each object over time.
- Generating appropriate interfaces. This involves different levels of warnings, as well as various human factors issues in the driver interface.

C. *Guide to the Specification Document*

The next sections of this document contain the specifications and explanatory text. The specifications themselves are in ***bold italics;*** explanatory text is in normal type face. Some of the specifications are listed as "optional". This means that the function being described is not crucial to the overall performance of the system, but, if supplied, it should perform as described in the optional specification. Typical optional specifications describe functions that will improve the predictions of bus or object motion, and thus help decrease nuisance alarms.

The appendices contain additional material, illustrations, and definitions. They are included in this document to aid in understanding the core specifications.

Further information on this project, and the data analysis leading to the specifications, is in the report "Development and Testing of Performance Specifications for a Next Generation Side Collision Warning System" and the papers listed in that report's bibliography.

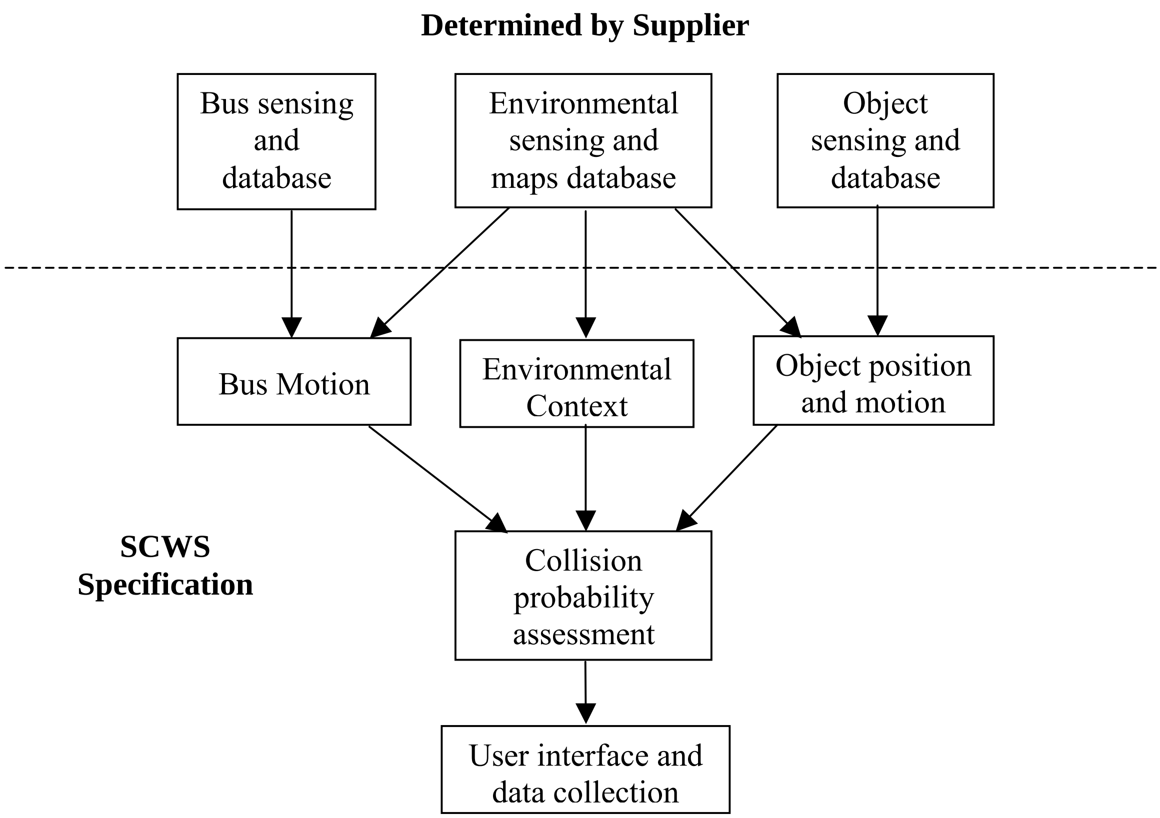
II. Scope

The performance specifications contained herein form the framework of requirements for specifying and evaluating a side collision warning system and implementing the broad framework outlined above. These specifications have been iterated over time and reflect the current thinking. It is anticipated that prototypes of a system will be built, tested and evaluated in phase two in both the simulation world and the real world to validate this set into a final set that could be sent out for quotations. Part of the commercialization to be conducted under Phase 2 will bring a complete bid package of specifications together to form the final set by year 2 which will be validated by year 3 for phase 2.

All binary variables such as on / off or class of objects are specified at 100 % accuracy rate. Any errors in a side collision warning system for these specifications may result in degraded system performance, but should not result in inoperability.

Figure 1 shows the organizational structure for the performance specifications. Appendix F shows, in tabular form, how the various specifications generate the data in the center of Figure 1, “Bus Motion”, “Environmental Context”, and “Object Position and Motion”. As can be seen, the hardware and sensor design of an SCWS is left up to the supplier; these performance specifications do not mandate a particular kind of sensor or database for performing the lowest-level functions. The SCWS Specifications contained herein involve the SCWS inputs, algorithm design, and outputs including the Driver Vehicle Interface.

Figure 1 - SCWS Specification Organization



These algorithms and DVI are shown in flowchart form in Figure 2. The specification organization shown in Figure 1 and the flowcharts shown in Figure 2 form the basic operating assumptions and baseline for an SCWS.

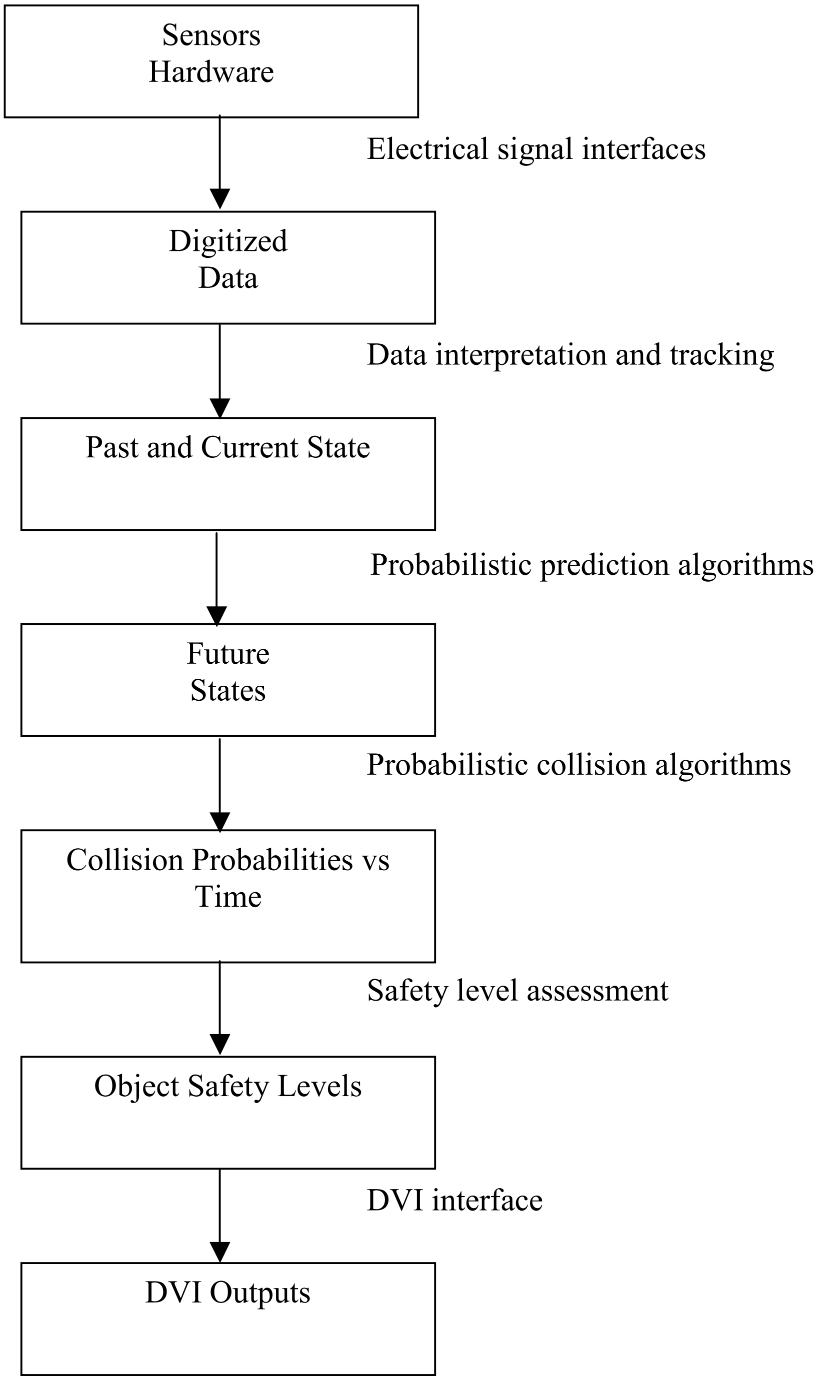


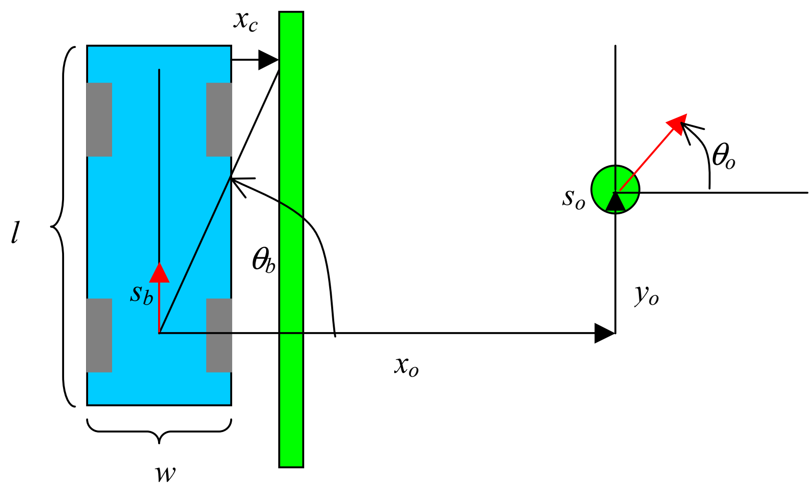
Figure 2 - Side Collision Warning System Flowcharts

Appendix D contains the data collection methodology and analysis used to begin the validation process of these performance specifications. Appendix E contains the potential Cost / Benefit Analysis for implementing an SCWS. Appendix F recapitulates the specifications in tabular form, showing how they tie to Figure 1; and Appendix G defines terms used in this document.

III. Transit Bus Coordinate Frame Definition

The performance specifications for an SCWS for transit buses are based on the following coordinate system as shown in Figure 3.

At t = 0 seconds, the origin of the coordinate system is the midpoint of the rear axle.



s_b = *the (scalar) speed of the bus*
θ_b = *direction of the bus velocity (=0 for t=0)*
$\dot{\theta}_b$ = *the yaw-rate of the bus*
x_o,y_o = *the position of the object relative to the midpoint of the rear axle*
s_o = *the speed of the object relative to the world*
θ_o = *the direction of the object velocity*
$\dot{\theta}_o$ = *the yaw rate of the object*
x_c = *the position of the curb with respect to the bus*
w = *the width of the bus*
l = *the length of the bus*

Figure 3 - Bus Coordinate System

IV. Performance Specifications

A. *Transit Bus Motion Measurement Requirements*

The SCWS must know the current bus motion as an input to predict the future bus location.

1. The SCWS shall measure current (see Figure 3)

a) Scalar speed sb of the bus to within 5 %

b) Yaw-rate $\dot{\theta}_b$ of the bus to within +/- 1 deg/sec

c) Acceleration of the bus [Optional]

B. *Transit Bus Status Requirements*

This information will be used for cues for future bus movement and environmental context. If the door is open, the bus is less likely to be moving and pedestrians expected in close proximity; if the right turn signal is on, the bus is likely to begin a right turn, etc.

1. The SCWS shall monitor the status of

a) Door open / closed

b) Right turn signal on / off

c) Left turn signal on / off

d) Hazard lights on / off

e) Brake actuation [Optional]

f) Throttle actuation [Optional]

g) Front wheel steering angle [Optional]

C. *Environment Context Requirements*

These environmental parameters affect the prediction of both bus movement and object movement. A bus is unlikely to cross a curb; a pedestrian on the sidewalk will behave differently than a pedestrian in the street; etc. None of these measurements guarantee future positions (busses do occasionally cross curbs, and the SCWS must take that into account), but they do affect the probabilities of motion and thus of collision. If the system has additional information, such as the bus's intended route and current location, it will be possible to predict upcoming turns. If the system knows about intersections and pedestrian crosswalks, it can take into account likely locations for crossing traffic.

1. The SCWS shall measure distance from the front right corner of the bus to the edge of a non occluded curb (x_c) that is less than 2 meters away to an accuracy of 5 cm or 2.5 %, whichever is greater.

2. The SCWS shall track curb location over time in order to determine the curb profile alongside the bus consistent with the accuracies in Specification C 1., A 1. a) and b)

3. The SCWS shall know the location of permanent blind spots for transit operators as shown in Figure 4.. The blind spots should be determined for the "average" driver with their head in the rest position with the mirrors properly adjusted.

4. The SCWS shall determine current transit bus map location [Optional]

5. The SCWS shall determine the location of other relevant road infrastructure such as:

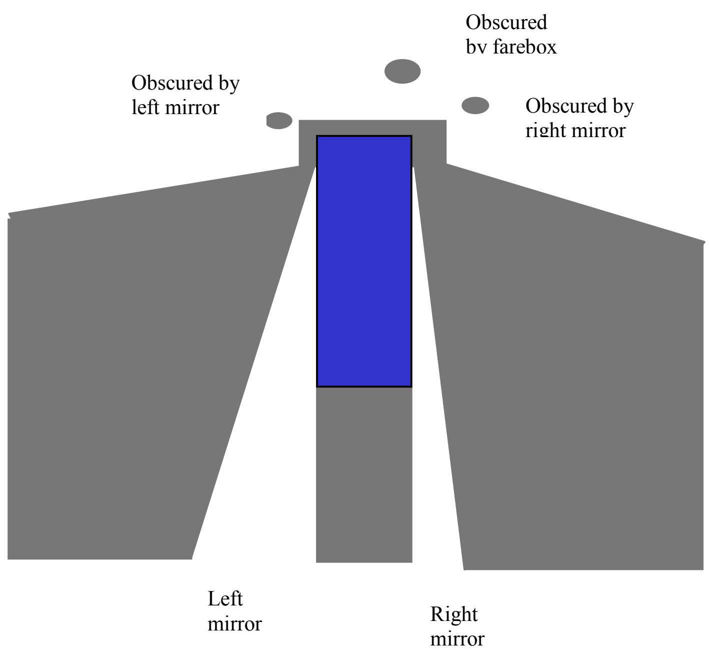
a) Intersections [Optional]
b) Upcoming turns [Optional]
c) Locations of bus stops [Optional]
d) Direction of travel (north, south, etc) [Optional]
e) Time of day [Optional]

6. The SCWS shall determine the location of temporary blind spots due to external objects in the operator's lines of sight. [Optional]

D. *Object Pose Measurement Requirements*

The SCWS needs to determine the location (pose) and motion of objects around the bus,

Figure 4 - Typical blindspots for a bus – the actual locations depend on the height of the dash, the location of the farebox, etc.



in order to be able to predict their future locations. It is particularly important to not only detect but also classify moving pedestrians and vehicles. Most objects are assumed to be fixed and their future locations will be based strictly on bus movement. Other objects may be moving, or may be currently stationary but capable of moving; hence determining object type will in some circumstances be crucial to predicting future position. The SCWS should at least categorize objects as pedestrians; vehicles; other moving objects; or currently fixed objects. Each of those classes of objects will have its own movement patterns. Vehicles move in well-defined ways and their motion will be used to predict future location. Pedestrians can move much more unpredictably, but still usually obey simple models relative to their position with respect to the sidewalk. Other moving objects could be dogs, or cyclists, or inanimate objects; it is very difficult to predict their movements.

Perhaps the most difficult specification in this section is detecting pedestrians that have fallen under the bus. This type of incident does not happen very often, but is very hard for a bus operator to detect and is very dangerous. Specification D.6 calls this out as a specific special case, since sensing underneath the bus may require very different sensors and algorithms than sensing next to the bus.

Sensing the velocity of objects near the bus is important in estimating their future positions. In some cases, such as a car, sensing their yaw rate (turning rate, related to curvature of their path) will provide an important additional cue to their future direction of motion.

1. ***The SCWS shall detect stationary objects within 2 meters of the sides of the bus, and extending forward at least 1 meter ahead of the front corners of the bus along its trajectory as shown in Figure 5***.

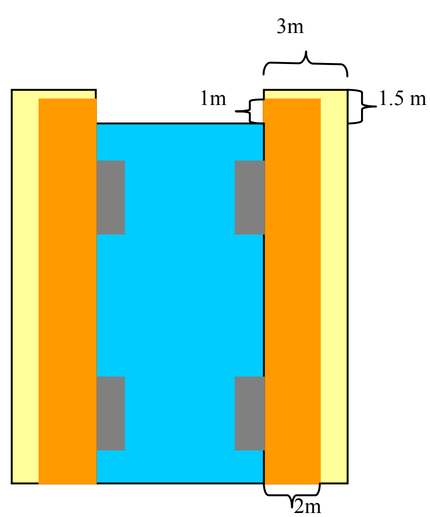


Figure 5 - Detection Area

2. The SCWS shall determine the longitudinal location (y_0) of stationary objects to an accuracy of 10 cm or 10 % of the lateral distance (x_0 – w/2) whichever is greater. The position shall be measured to the nearest point on the object. (Figure 3)

3. The SCWS shall determine the lateral location (x_0 – w/2) of stationary objects to an accuracy of 5 cm or 5 %, whichever is greater. The position measurement shall be the shortest distance from the side of the bus to the nearest point on the object.

4. The SCWS shall detect moving objects within 3 meters of the side

of the bus, and within 1.5 meters ahead of the bus along its trajectory as shown in Figure 5.

5. ***The SCWS shall be able to discriminate between the following moving objects 95 % of the time.***
    a) *Pedestrians*
    b) *Vehicles*
    c) *Other moving objects such as bicycles*

6. ***The SCWS shall detect pedestrians that have fallen partially under the bus forward of the wheels.***

7. ***The SCWS shall measure the position ((x_0 – w/2), y_0) of each moving object to an accuracy of 10 cm or 10 %, whichever is greater (Figure 3).***

8. ***The SCWS shall measure the scalar speed of each moving object to an accuracy of 5 cm / sec or 5 %, whichever is greater.***

9. ***The SCWS shall measure direction of the object velocity to within 5 degrees (Figure 3).***

10. ***The SCWS shall measure the yaw rate of the object velocity [Optional]***

E. *Collision Probability Requirements*

All of the above specifications deal with data acquisition, either by sensing or by database retrieval. At this point, the SCWS has all the inputs it needs. The next step is to predict the motions of the bus and of objects for up to 5 seconds, then to assess the probability of collision. Several approaches are possible (predictive algorithms, precompiled lookup tables, etc, for examples see Appendix A and Appendix B); but this specification properly states the function and leaves the implementation to the developer.

1. ***The SCWS shall determine for the times 2, 3, and 5 seconds in the future the probability of collision. "Probability of collision at time t" is defined as the probability that a collision will have occurred some time between 0 and t; that is, it is the cumulative probability that a collision occurs some time during that interval..***

2. ***The SCWS shall determine if a collision is occurring or has occurred***

F. *Warning Generation Requirements*

Once a collision is possible, the system needs to generate the appropriate safety level. In some cases, the safety level may be to a third party, such as a loudspeaker warning a pedestrian who is walking into the side of the bus. In most cases, the warning will be to the bus operator, along a sliding scale of urgency. It is very important that the system generate these levels when appropriate; it is also vital that the system not generate nuisance alarms or false positives, which could lead to lack of attention by the operator. Appendix C defines "false positive" and "false negative" for this application. See

Appendix A.III for potential ways to reduce nuisance alarms, and Appendix A.V for a way to determine safety levels.

This specification defines 4 safety levels, from “aware” (no dangerous situation) to “alert” to “warn” to “notify”. The algorithm for determining which of those safety levels applies to the current situation is somewhat complex because it must take into account both the probability that a collision will occur and the time to collision. If a collision is highly likely with no intervention, but not for many seconds, then the safety level is low; if a collision is moderately likely in the next few seconds, the safety level may be higher. The relationship between time, probability of collision, and safety level, is given as a graph. Since collisions with pedestrians, vehicles, and fixed objects all have different typical severities, the calculation is different for each object type, and therefore the specifications present three separate charts.

The specifications that mention a “third party” are primarily intended for warnings to pedestrians. Some transit vehicles are equipped with external annunciator systems that broadcast the bus route and destination; the speaker systems of those vehicles could be used to warn pedestrians, if any are too close, that the bus is about to start moving.

The intent of specification 6 is that the most urgent warning wins: if there are two objects with different safety levels, we want the highest safety level to drive the DVI

a) ***The SCWS shall generate the appropriate safety level Aware – No incidents are likely.***
b) ***Alert – Potential obstacles.***
c) ***Warn – Collision is likely without evasive action.***
d) ***Notify –An incident has occurred.***

2. The safety level determination will be based on object type, probability of collision, and time to collision, as given by the following charts

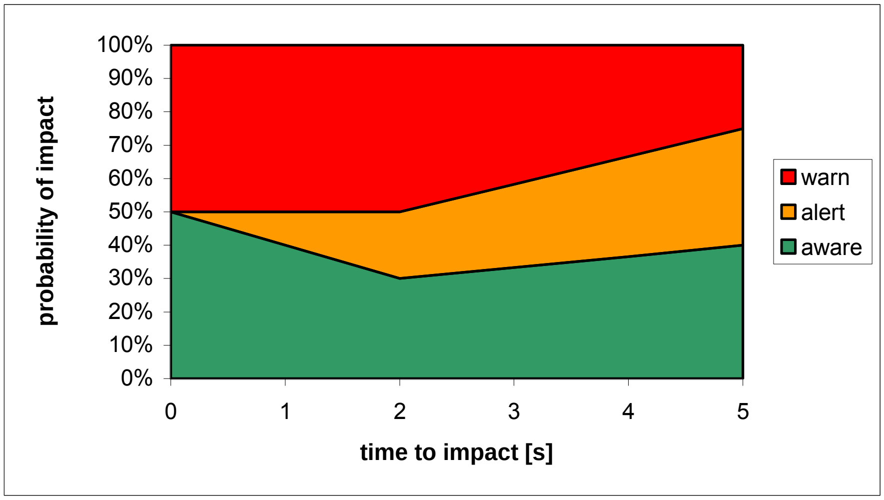


Figure 6 - Probability versus Safety Level Diagram for Pedestrians

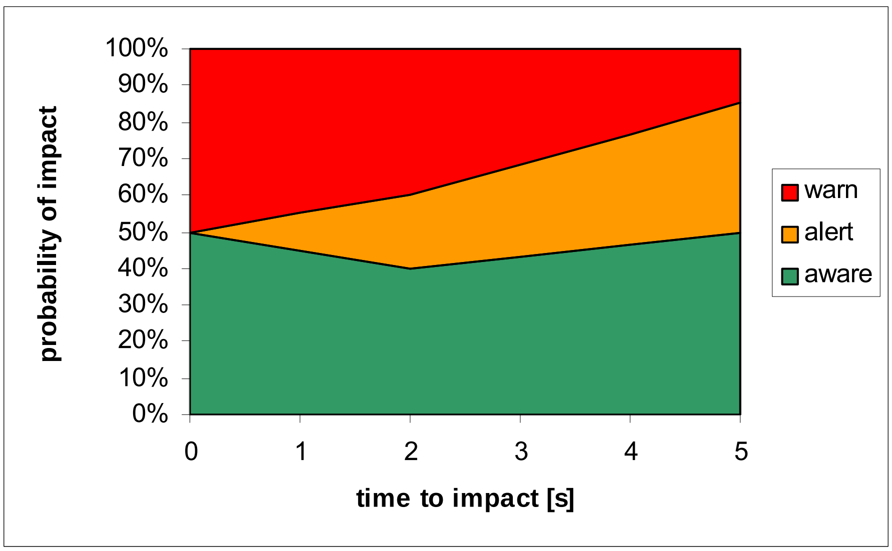


Figure 7 - Probability versus Safety Level Diagram for Vehicles

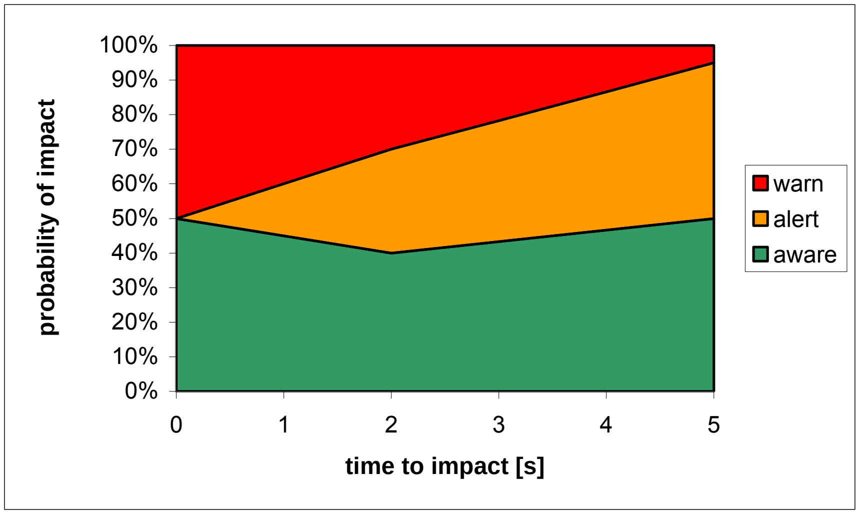


Figure 8 - Probability versus Safety Level Diagram for all other Objects

3. ***The SCWS shall compensate for computational latency in the probability calculation in generating the safety level at the correct time***

4. ***The SCWS shall determine if a reaction by a third party is needed and feasible for each event. [Optional]***

5. ***The SCWS shall generate the appropriate safety level for each potential impact where the reaction by a third party is feasible. [Optional]***

6. ***The SCWS shall take into account all potential safety levels, and shall output the most urgent safety level for each side of the bus to the DVI.***

7. ***The SCWS algorithms shall be designed to limit nuisance alarms by identifying situations that occur in the bus environment, but do not lead to incidents. See Appendix A.III for the minimum set to implement.***

8. ***The SCWS shall generate less than 5% False Positives as defined in Appendix C.***

9. ***The SCWS shall generate less than 5 % False Negatives as defined in Appendix C.***

10. ***The SCWS shall provide hysteresis in generating safety levels to prevent toggling of the DVI Inputs.***

G. *DVI Requirements*

The most important part of the user interface is advising the operator of the various levels of safety in a way that is conducive to assisting the operator to avoid any incidents. These safety levels vary from Aware to Warn, plus Notify after an incident has occurred.

1. The SCWS DVI shall provide operator adjustments for volume and brightness controls.

2. The SCWS DVI shall provide an indication that the SCWS is operational. This indicator shall be based on the following self tests:

a) Processor heartbeat present [Computer based systems only]
b) Memory Checksum pass [Computer based systems only]
c) Sensors are functional
d) Vehicle state inputs are functional

3. The SCWS DVI shall provide for the following four safety levels:

a) Aware – (No incidents are likely.) System Operational light is on
b) Alert – (Potential obstacles.) As a minimum a light or LED is illuminated on the appropriate side of the bus.
c) Warn – (Collision is likely without evasive action.) Sound is generated on the appropriate side of the bus.
d) Notify –(An incident has occurred.) Audio message and light / LED indicating an incident has occurred. These indicators are not to be adjustable by the operator.

H. *Recording Requirements*

From a scientific and safety standpoint, it would be important to record potential or actual accidents. Transit agency operating policies may override the scientific concerns and cause this part of the system not to be implemented.

1. The SCWS shall record all, some or none of the following information whenever the SCWS moves from Aware to any other state; moves from Alert to Warn or Notify; or moves from Warn to Notify: [optional]

a) Video frame with a resolution of at least 320X240
b) Vehicle State Data
c) Object State Data and Object Type
d) Time and location of incident
e) SCWS Safety Level

2. The SCWS shall record all, some or none of the following information 10 seconds before and two seconds after the SCWS moves to Notify [optional]

a) Five seconds of Video with a resolution of at least 320X240 at a minimum of 3 Hz [Optional based on Transit Agency restrictions]
b) Vehicle State Data
c) Object State Data and Object Type
d) Time and location of incident
e) SCWS Safety Level

I. *Operational Requirements*

These specifications will be determined in the next phase of this project to incorporate other standard documents for procuring electronic equipment to be used on transit buses as applicable based on input from commercial suppliers and the transit industry.

1. The SCWS shall function in the normal operational environment of transit buses

a) Shock
b) Vibration
c) Temperature
d) Humidity
e) Weather (rain, snow, etc)
f) Bus Wash
g) Electromagnetic Interference

2. The SCWS shall be operational 95% of the time

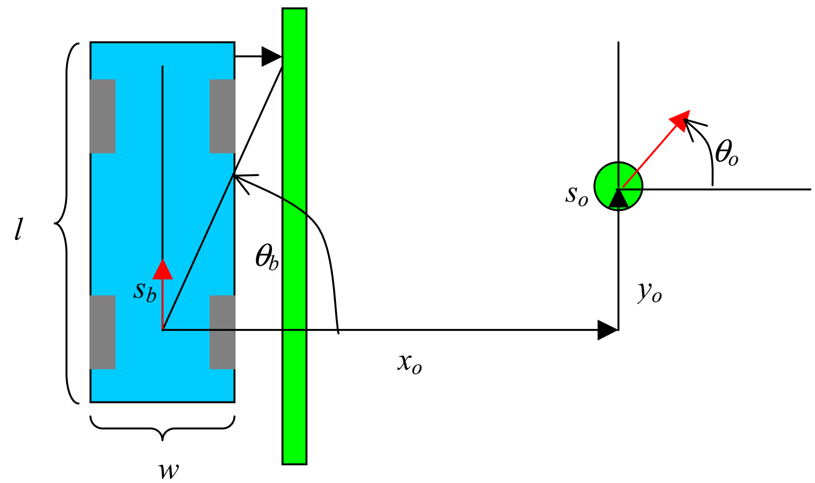
3. The SCWS shall not adversely affect other onboard systems and normal transit bus operation

4. [These requirements should include the requirements that the transit bus agency has for any electrical system that is installed on the bus]

Appendix A - Probability Calculations

I. Coordinate System

At t = 0s the origin of the coordinate system is the midpoint of the rear axle.



The side collision warning system (SCWS) shall determine the following within their respective errors.

1. the (scalar) speed of the bus s_b
2. the yaw-rate $\dot{\theta}_b$ of the bus
3. the direction of the bus velocity θ_b (=0 for t=0)
4. the position (x_o,y_o) of the object relative to the midpoint of the rear axle
5. the speed of the object s_o relative to the world
6. the direction of the object velcity θ_o
7. the yaw rate $\dot{\theta}_o$ of the object
8. the position of the curb x_c with respect to the bus

II. Calculation of probability of collisions

The probability of collision formula can be written as follows:

$$p(t) = \int_{allX} w(X,t)dX$$

where:

$w(X,t) = w(X,t_0 = 0)$, if the path(X) intersects the bus between time t_0=0 and t and 0 everywhere else.

X = vector of all coordinates and their derivatives (speeds, yaw-rate, etc.) which are being considered at time t_0=0.

path(X) = the path of the object w.r.t. the moving bus given the initial conditions X.

$w(X, t_0 = 0) =$ the weight determined by the errors of the elements of X, assumptions about unmeasured quantities and the environment:

$X=(x_1,x_2,\ldots)$ with errors $\Delta X=(\Delta x_1,\Delta x_2,\ldots)$

Therefore:

$$w(X, t_0 = 0) = S_1(x_1, \Delta x_1) \cdot S_2(x_2, \Delta x_2) \cdot \ldots G_1(a_1) \cdot G_2(a_2) \cdot \ldots w_1(E_1, X) \cdot w_2(E_2, X) \cdot \ldots$$

where

S_n = the error function of the measured coordinate x_n

G_n= TBD distribution functions of the unmeasured accelerations a_n= $\ddot{\theta}_b$, $\ddot{s}_b$, $\ddot{\theta}_o$, or $\ddot{s}_o$

w_n = weighting functions taking e.g. knowledge of the environment into account.

Two examples are included in Appendix B.

III. Rules to limit nuisance alarms

The SCWS shall take following weighting functions into account by modifying the probability calculation in the previous section:

A. *Curb Position*

E_1: position of object w.r.t. the curb

$$w(E_1, X) = \begin{cases} 2/N & \text{if the object is always on the curb between time } t_0\text{=0 and t} \\ 0.2/N & \text{if the object is on the curb at } t_0\text{, but not at t} \\ 1/N & \text{if the object is not on the curb at } t_0 \end{cases}$$

Where N is an appropriate normalization factor.

B. *Status of indicator lights, status of doors*

1. *E_2: Hazard lights on, bus stopped*

$w(E_2, X) = \text{TBD}$

2. *E_3: Right turn signal on*

$w(E_3, X) = \text{TBD}$

3. *E_4: Left turn signal on*

$w(E_4, X) = \text{TBD}$

4. *E_5: Status of doors*

$w(E_5, X) = \text{TBD}$

C. *Increase probability if object is in blind spot*

E_6: location of object inside or outside a permanent or temporary blind spot

$w(E_6, X) = \text{TBD}$

D. *Other modifications of probability calculation*

The SCWS may take other rules about the environment, behavior of the bus or object into consideration and include the appropriate weighting functions $w(E_n,X)$ as long as it can be shown, that this inclusion reduces the number of nuisance alarms.

The SCWS may use approximate algorithms to calculate the probability p(t) as long as it is within 10% of the exact solution.

The SCWS may measure more information about the environment, bus and the object (e.g. acceleration, extension of the object) or know more about the environment, bus and the object (e.g. dynamic properties) and incorporate it appropriately into the path calculation.

IV. Occurrence of Collision

For t=0 the probability tells us if a collision is occurring or not. In the absence of measurement errors $p(t=0)$ = 0% or 100%, then only the location of the object needs to be known: if the position of the object is within the bus, a collision is occurring. This simple calculation is not only complicated by the measurement errors, but also by the fact, that measurements and calculations are done at a finite frequency. The occurrence of collision should therefore be determined in the following way:

If $p(t=1/f)$ > 50% a collision is occurring

where f = the update frequency, i.e. the frequency at which the calculations are done.

V. Determining safety level

Human Factors play the largest role in determining when to warn operators and for which situations. The following charts illustrate the following principles for generating the various safety levels.

- For time = 0, the probability should be 0 or 100%
- For time from 0 to 2 seconds, there is not enough reaction time for warning, but an alert situation could turn into one, so the curve is straight for warnings but drops for alerts
- For time 2 – 5 seconds, the probabilities relating to safety levels are linear.
- For time > 5 seconds, there is too much inaccuracies or possibilities to make generating safety levels meaningful

These charts show the general shape for associating safety levels with probabilities of collision. These charts will be used in phase II of this project in both simulations and road tests and adjusted based on the results.

The resulting charts illustrate for each [t,p(t)] the safety level for the three categories of objects encountered.

The safety level for the considered object is the highest safety level of all [t,p(t)].

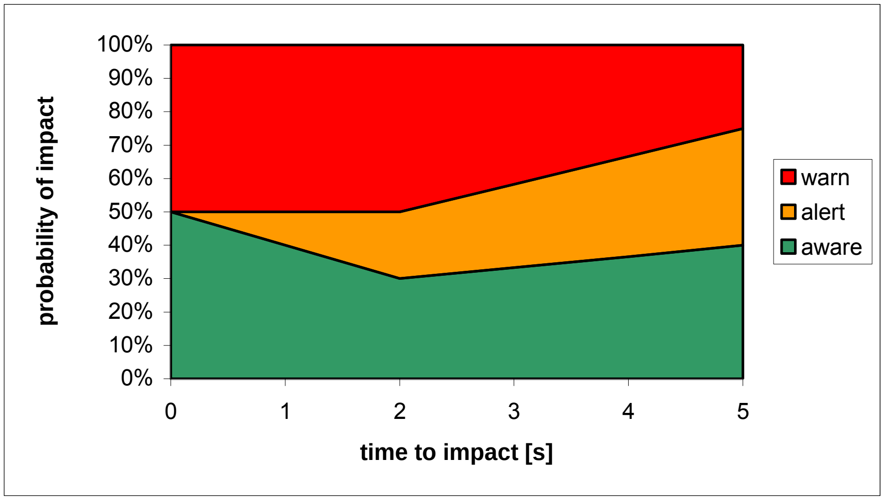


Figure 9 - Probability versus Safety Level Diagram for Pedestrians

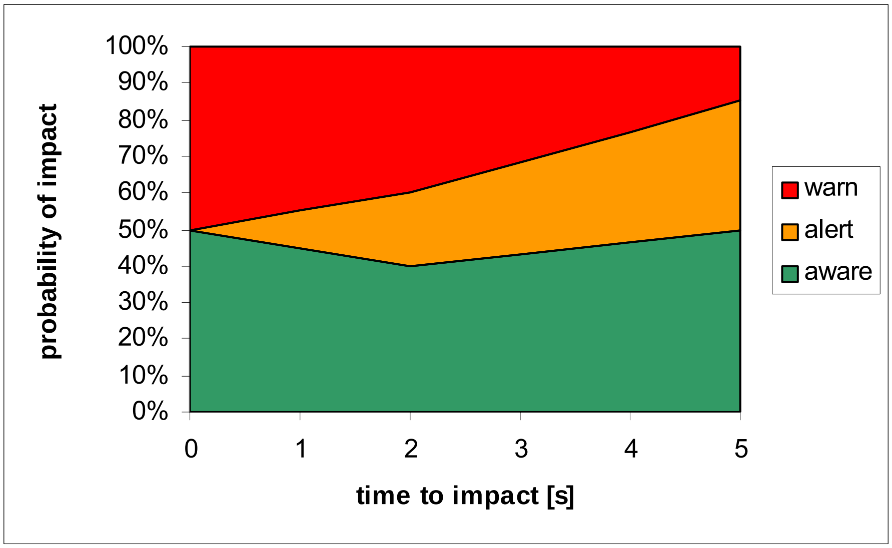


Figure 10 - Probability versus Safety Level Diagram for Vehicles

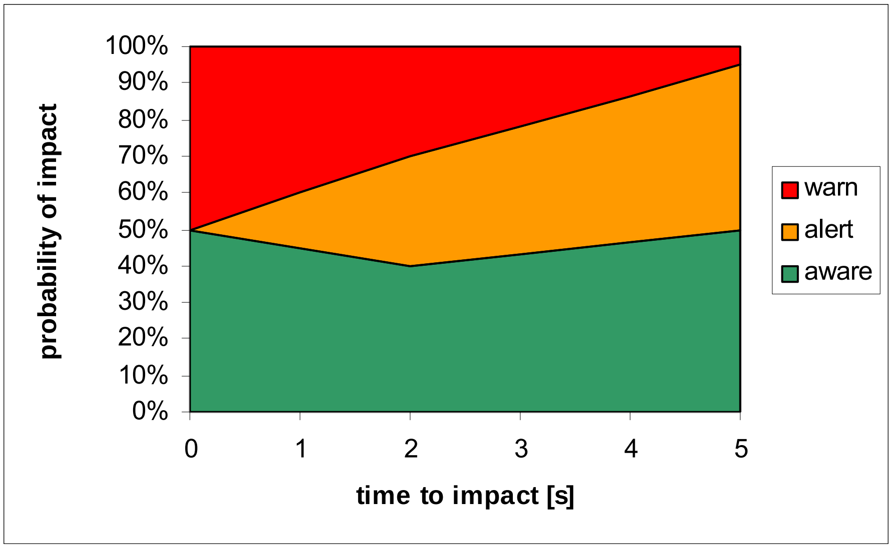


Figure 11 - Probability versus Safety Level Diagram for all other Objects

Appendix B - Probability of Collisions Example

I. Formal derivation

Let the rest frame of the bus be the frame of reference and the time dependent location of the object be described by two coordinates:

Equation 1 $$\vec{X}(t) = (x_1(t), x_2(t))$$

If $\vec{X}(t)$ is infinitely differentiable then it can be expressed at any time t as (polynomial expansion about the time $t_0=0$):

Equation 2 $$\vec{X}(t) = \vec{X}(t_0) + \dot{\vec{X}}(t_0) \cdot t + \frac{1}{2}\ddot{\vec{X}}(t_0) \cdot t^2 + \ldots$$

Therefore, if at t_0 all the time derivatives of $\vec{X}(t)$ are known, $\vec{X}(t)$ is known for any time in the future.

In the real world it is of course not possible to know the location of an object observed by a CWS for all times in the future for following reasons:

1. Not all time derivatives are known.
2. The knowledge of any derivative has an uncertainty.
3. $\vec{X}(t)$ of real objects are most times not infinitely differentiable.

The first two reasons come from the limitation of sensors. An example of the third is a vehicle driving straight and at some point the driver decides to make a turn; this decision will turn out to be a discontinuity in one of the time derivatives.

II. Practical implementation

Even though Equation 2 cannot be applied exactly, it can be used as an approximation.

1. Knowledge of the kinematics of the bus and the object can reduce the possible values of certain time derivatives (e.g. the maximum power of the bus engine puts an upper limit on the possible accelerations of the bus).
2. The uncertainties of a derivative at time t_0 can be propagated into an uncertainty of location at time t.
3. Models of driver behavior can identify times where discontinuities might occur.

A. *Coordinate system*

It can be advantageous to choose a coordinate system in which the relevant equations are simplified. In the case of a transit bus one should take its kinematic constraints into account. The rear axis of a bus, as is the case for most vehicles, can move forward or backward, but not sideways. This fact is reflected in the coordinate system (Figure 3). If the bus driver does not change the state of the bus, i.e. does not accelerate or turn the steering wheel, s_b and $\dot{\theta}_b$ remain constant and all other derivatives are zero.

III. Example 1 – Bus Driving Straight

In the following example we exaggerated the errors and oversimplified the algorithm in order to better visualize the method of calculating the probability.

A bus drives straight with a speed of 5 m/s and another vehicle drives straight, perpendicular to the bus with a speed of 4 m/s. Each velocity is measured to an accuracy of 0.8 m/s. At time t=0s the vehicle is located 10 m in front and 15 m to the right side of the bus. The location and velocity of the vehicle with respect to the bus is shown in Figure 12.

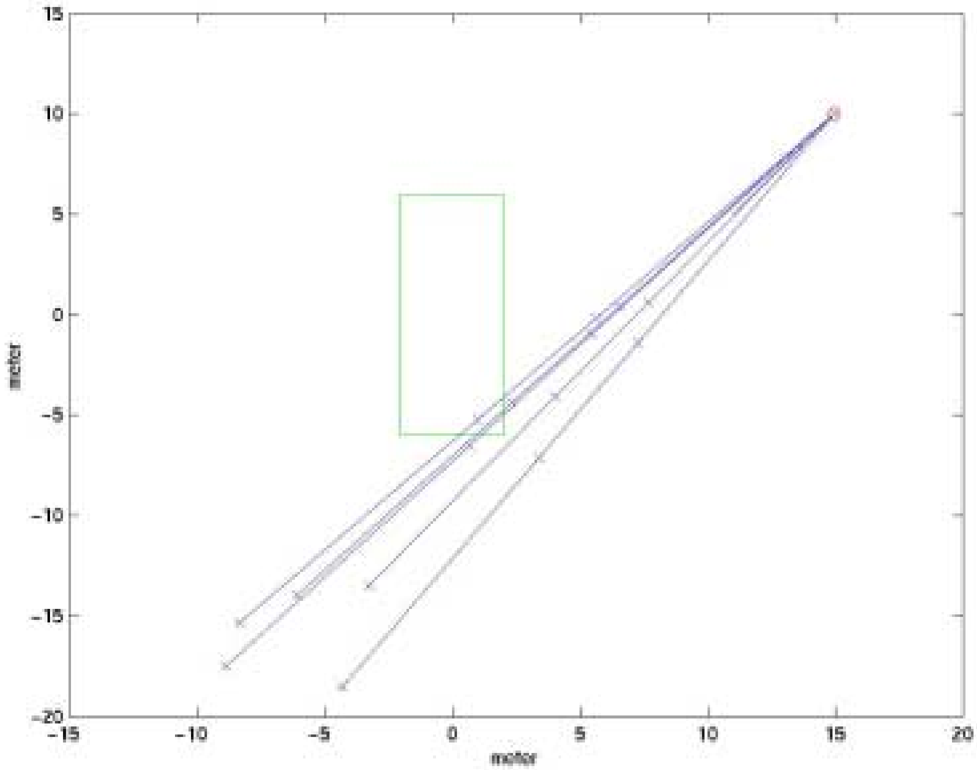


Figure 12 - Bus and vehicle in the rest frame of the bus. The velocity of the vehicle is shown as a red line (distance traveled in 1 s). The blue lines are 5 tracks with randomly chosen velocities, the tracks are marked at 2, 3, and 5 seconds.

The probability of collision is calculated numerically and with the help of random numbers. Five tracks are constructed by randomly choosing a bus speed between 4.2 and 5.8 m/s and a vehicle speed between 3.2 and 4.8 m/s. The resulting possible locations of the vehicle corresponding to these 5 tracks at 2, 3, and 5 seconds can be seen in Figure 12.

At 2 seconds none of the tracks overlap the bus and therefore p(2s) = 0%.

At 3 seconds 2 of the tracks overlap the bus (one is inside the bus and one has just passed through) and therefore p(2s) = 40%.

At 5 seconds 3 of the tracks overlap the bus and therefore p(2s) = 60%.

IV. Example 2 – Bus Turning Right

In this example, the bus is turning right while an object is moving from right to left:

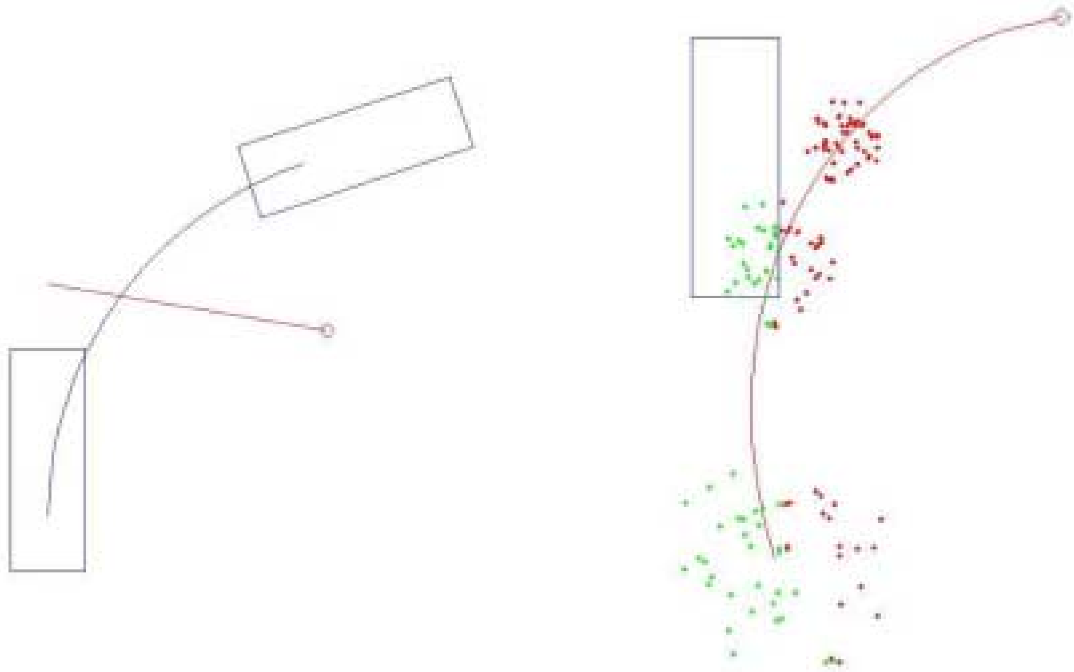


Figure 13 - The bus is turning right and an object is moving from right to left. The left image shows the situation in the frame of the environment and on the right it is shown in the frame of the bus, the lines are the paths the bus or object traveled within 5s. The dots indicate the possible locations of the object for 2s, 3s, and 5s. The light green dots indicate that the object is hitting or has hit the bus.

The poses and their errors are:

Bus speed = 5 ± 0.4 m/s
Radius of curvature = 20 ± 1 m
Object location x = 15 m
Object location y = 10 m
Object speed in x = -3 ± 0.8 m/s
Object speed in y = 0.5 ± 0.8 m/s

The parameters have been varied randomly within their errors and the resulting locations of the object at 2s, 3s, and 5s are shown in Figure 13 as dots in the right image. The dots colored in light green are the paths where the object hits or has hit the bus. The (approximate) probability of collision for the three times is the number of green dots divided by the total number of dots:

p(2s) = 0%, p(3s) = 54%, p(5s) = 62%

These probabilities can be plotted into Figure 11:

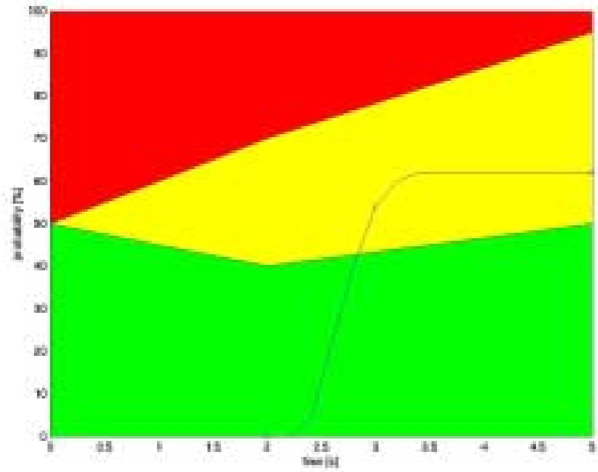


Figure 14 - The calculated probabilities overlaid on the aware/alert/warn diagram (Figure 8). The probabilities for 2s, 3s, and 5s are marked with 'x'.

The probabilities reach up to ‘alert’, but not up to ‘warn’, so the system should give the driver an ‘alert’.

Appendix C - Quantifying false positives and false negatives

This appendix quantifies what is meant by "there should be less than 5% of false positives" and "there should be less than 5% of false negatives" The Aware situation includes the cases where there are no potential obstacles. False positives are "overwarn" situations where the SCWS provides an alarm that is more severe than the situation warrants. Conversely, a false negative can be thought of as an "under warn" situation, where the SCWS provides an alarm that is less severe than the situation warrants. Lastly, the "correct" situations are the "correct warn" situations where the system accurately diagnoses the hazardous situation.

We therefore can define false positives / negatives as follows:

Alarm generated→ Actual situation↓	Aware	Alert	Warn	Notify
Aware	C_{11}	FP_1	FP_2	FP_3
Alert	FN_1	C_{22}	FP_4	FP_5
Warn	FN_2	FN_3	C_{33}	FP_6
Notify	FN_4	FN_5	FN_6	C_{44}

Where C=correct, FP=false positive, FN=false negative

Suppose we collect data with the system operational and have N alarms with the following distributions:

Alarm generated→ Actual situation↓		Aware	Alert	Warn	Notify
		n1	n2	n3	n4
Aware	m1	S11	S12	S13	S14
Alert	m2	S21	S22	S23	S24
Warn	m3	S31	S32	S33	S34
Notify	m4	S41	S42	S43	S44

Where

n1 = S11+S21+S31+S41
m1 = S11+S12+S13+S14, etc.
N = n1+n2+n3+n4 = m1+m2+m3+m4

Typical ways to specify and measure the performance of the SCWS is by knowing the true number of hazards/hazardous situations. This number N serves as the denominator when defining nuisance alarms and correct "hits." Obtaining this "ground truth" information can be done using a simulator, where the hazards are controlled and counted, or coding a video of a field operational test.

False positives would be the sum of S12+S13+S14+S23+S24+S34

False negatives would be the sum of S21+S31+S32+S41+S42+S43

Therefore the percentage of false positives would be:

$$(S12+S13+S14+S23+S24+S34) / N \text{ which should be } < 5\%$$

And the percentage of false negatives would be:

$$(S21+S31+S32+S41+S42+S43) / N < 5\%$$

leaving the correct levels to be

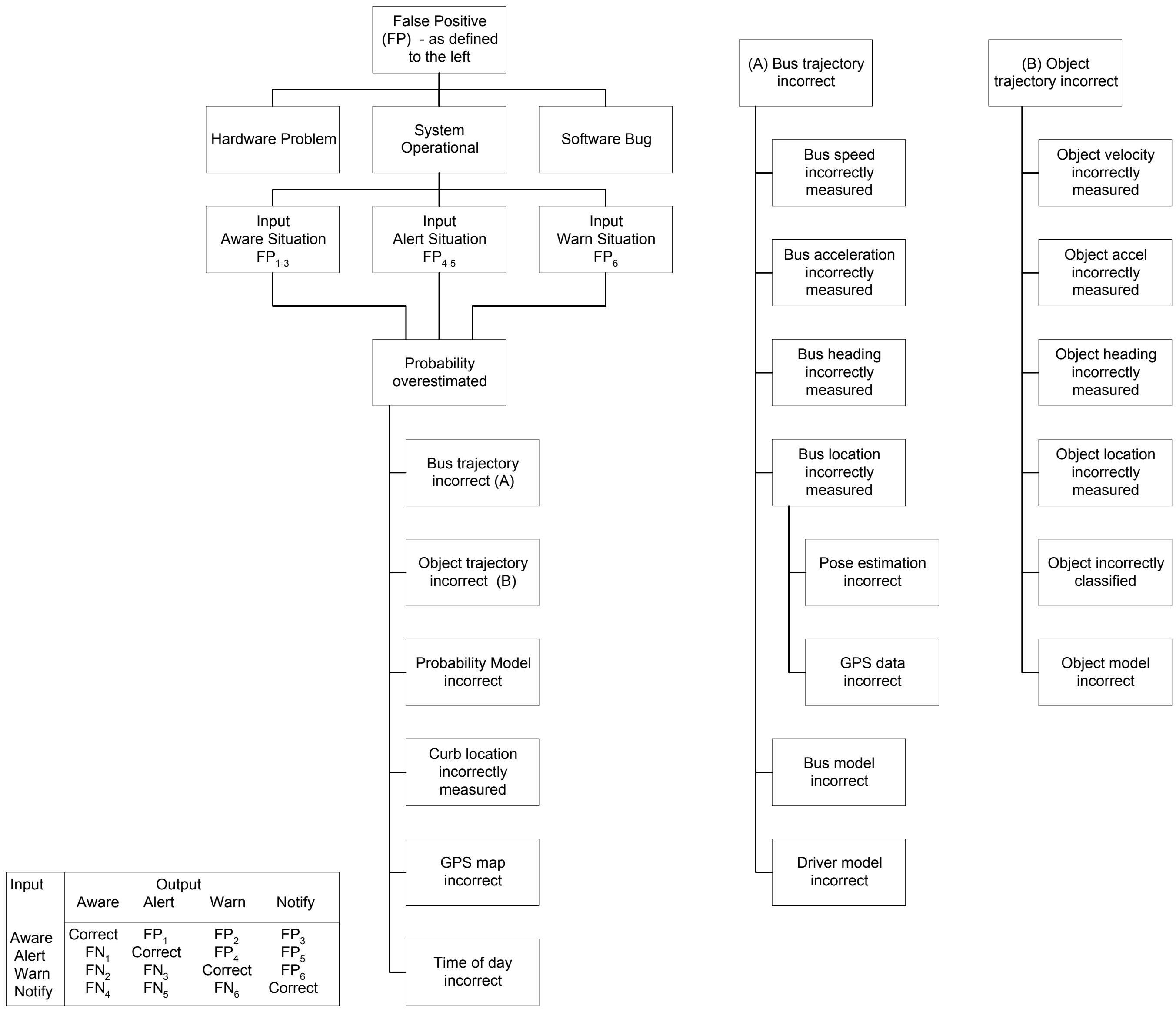
$$(S11+S22+S33+S44) / N > 90\%$$

Independent of the update rate each alarm would only be counted once, as long as the display is *continuously* activated. In situations with multiple object only the object posing the greatest threat at that moment is counted.

This methodology does not distinguish between different levels of falseness, e.g. a false positive where the system thinks there is an object but there is none is much more serious than a false positive where the system thinks the object is 0.9 m away but in actuality it is 1.1 m away (with the limit between the two alarm levels at 1m).

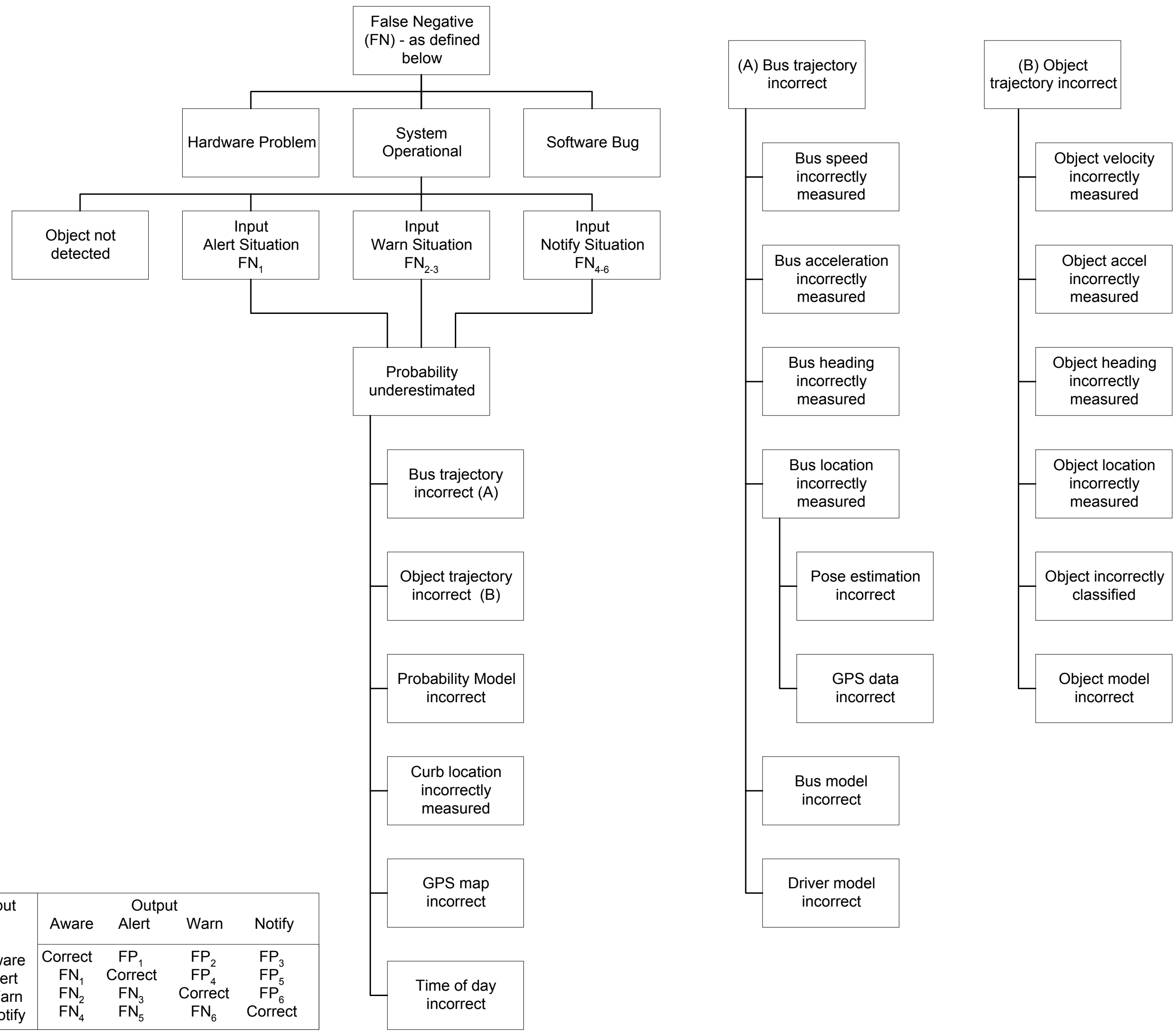
Another way to specify false positives and negatives is the number false events / hour. This would be good to look at in phase 2 of this project by asking bus operators if they think they would be more tolerant of nuisance alarms in some environments and less tolerant in others.

Figures 12 and 13 illustrate two simple fault trees for false positives and false negatives.



Input	Output: Aware	Alert	Warn	Notify
Aware	Correct	FP_1	FP_2	FP_3
Alert	FN_1	Correct	FP_4	FP_5
Warn	FN_2	FN_3	Correct	FP_6
Notify	FN_4	FN_5	FN_6	Correct

Figure 15 - Simplified False Positive Fault Tree



Input	Output			
	Aware	Alert	Warn	Notify
Aware	Correct	FP_1	FP_2	FP_3
Alert	FN_1	Correct	FP_4	FP_5
Warn	FN_2	FN_3	Correct	FP_6
Notify	FN_4	FN_5	FN_6	Correct

Figure 16 - Simplified False Negative Fault Tree

Appendix D - Side Collision Warning System: Data Analysis

I. Introduction

In the fall of 2001 we mounted sensors on the right side of a bus and collected data about traffic situations occurring on this side of the bus[1]. We built a database using the data collected from the transit bus sensors and data recorded simultaneously from the specially mounted sensors. In this report we present two analyses that draw on this database. Section II describes the installation and sample data collected, Section III shows what information and algorithms are necessary to correctly classify situations as safe or unsafe. Section IV gives an example on how a rule can be found, which can help predict the movement of the bus.

II. Installation of data collection system

A. *Hardware Description*

Three sensors were installed on the outside of a low-floor transit bus: a SICK laser scanner, a curb detector consisting of a laser and a camera, and a video camera.

Figure 17 - Bus before the installation of the sensors. The arrows point to the locations where the camera and the laser scanner will be installed.

The electronics was located in the inside of the bus above the left front wheel.

[1] See "Side collision warning system: Data collection during transit operations"

Figure 18 - The installed camera and laser scanner

Figure 19 - In the left the front bumper of the bus is shown with a small slit (red arrow) where the laser light exits. On the right the underside of the bumper is shown with the laser of the curb detector visible (blue arrow).

The electronics was interfaced with the Clever Devices™ Annunciator system, the Dinex™ multiplex system, the DDEC-IV engine controller and two single axis gyros within the Electronics Cabinet. The information recorded from these systems was: front door open/closed, hazard lights on/off, heading, speed, pose (yaw and pitch), temperature, throttle, acceleration pedal position, engine load, engine torque, brake pressure, and engine RPM.

Videotapes were made from the video camera. Curb information was collected at 30 Hz. Data from the SICK laser scanner was acquired at 6 Hz, GPS at 1 Hz, front door and hazard lights were only recorded when a change occurred, and the others were collected at 10 Hz.

Figure 20 - Electronics Console

B. *Sample data*

The (not yet calibrated) data for one instance in time can be seen in the following figure:

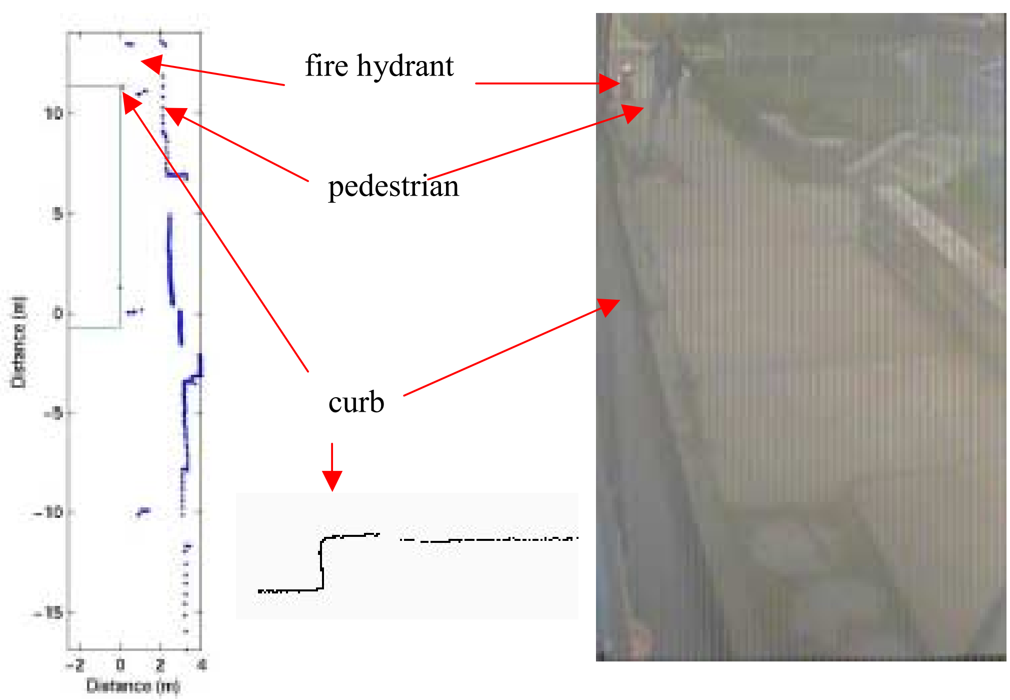


Figure 21 - Sample Data

To the right one can see video image showing several people on the sidewalk on the side of the bus. Besides the sidewalk is a grassy slope and in front of the bus, barely visible, is a fire hydrant. All these can be seen by the laser scanner and are shown as blue points on the left graph. In the middle the profile of the curb is displayed, as it is seen by the curb detector. The curb detector determined the distance of the curb to the bus and the curb is shown as a red dot in the left graph. The following additional information was also recorded.

GPS Position	40.46137 N 79.89477 W	**Front Door**	Open
Heading	18^{o}	**Hazard Lights**	On
Yaw Rate	0.0305 deg/sec	**Accelerator Pedal Position**	0.0%
Pitch Rate	0.03355 deg/sec	**Engine RPM**	697.0
Speed	0.0 MPH	**Output Torque**	243.9 Nm
		Engine Load	44.5%

III. Comparison of full and simplified algorithms

A. *Manual Classification from Video*

In order to establish ground truth, for a time interval of 30 minutes we manually classified all objects at the right side of the bus with the help of the video images. The bus was driving in the suburbs for 15 minutes and in downtown Pittsburgh the other 15 minutes. Only objects within approximately 2 meters of the side of the bus were counted. We distinguished between three bus maneuvers: cruising, turning right, and being stopped at a bus stop. There were no objects close to the right side of the bus while the bus was turning left. The result is tabulated in Table 1.

About half of all the objects encountered are actually on the curb. The great majority of objects on the street are parked cars. Most of the pedestrians on the street are there because they are entering or leaving the bus. Only two pedestrian were on the street while the bus was cruising. The first person was not on the curb because he was crossing at an intersection, walking parallel to the bus. The video showed that the second person was obviously intending to cross the street the bus was traveling on. Of everything encountered in these 30 min, only this one person intending to cross the street warranted a safety level higher than the baseline “no danger” level.

B. *Determining the severity of the situation*

The full algorithm to determine the safety level for a situation is written in Appendix A. In this section we want to investigate what simplified algorithms can achieve, when the full calculation of probability of collision is needed, and how important and useful different kinds of information are.

A proximity sensor and the curb detector together can determine if an object is on the curb or not. If one assumes that the situation is safe as long as things are on the curb or even on the edge of the curb, then already half of the situations in Table 1 can be determined to be safe.

	Object \ bus movement	Cruising	Turning right	Stopped	Total
On curb	Pedestrian	10[a]	3[a]	35[a,c]	199
	Mail box, trash can, etc.	26[a,b]	2[a,d]	3[a,c]	
	Tree, telephone poll, etc.	20[a,b]	4[a,d]	0[a,c]	
	Sign post, fence post, etc.	72[a,b]	10[a,d]	4[a,c]	
	Fire hydrant	8[a,b]	2[a,d]	0[a,c]	
Off curb	Parked car	70[b]	2[d]	2[c]	100
	Pedestrian	1[e]+1	0	15[c]	
	Vehicle in traffic	4	0	5[c]	
Total		212	23	64	299

Singular situations (bus was always cruising):

- Hedge beyond the curb[b]
- Sign on the street[b]
- Eight barrels blocking off a bus stop[b]
- Pedestrian on the edge of the curb[a]
- Tree hanging over the curb[b]
- Construction barrels on street[b]
- Concrete barrier[b]
- Metal barrier (on bridge)[b]

Total	307

Table 1 - Objects at the side of the bus. The letters a-e indicate which algorithms were used to correctly identify the severity of the situation (see text).

Fixed objects are no hazard if they are on the side of the bus and the bus is going straight. A sensor which can determine if objects are moving and an internal sensor which measures the heading of the bus provide the data to allow the system to evaluate these situations, in our example the majority of the remaining cases. Obviously, no warning or alert needs to be given to the driver when the bus is stopped, a situation easy determined by a speedometer.

To evaluate two parked cars encountered by the bus while the bus was turning right one needs more information than provided by the table. One needs to look at the trajectory of the bus and see, if the sweeping motion of the bus will cause a collision.

The person standing on the street intending to cross the street warrants an ‘alert’. It is necessary to identify the pedestrian as such as well as determining that he is not on the curb. This case emphasizes the importance of determining the location of the curb. But the location of the object with respect to the curb needs to be combined with a pedestrian detection and the knowledge that most people on the street intend to cross it.

The remaining cases of the pedestrian off the curb and the vehicles driving alongside the bus need the full calculation of determining the probability of collision.

The information obtained from the sensors used is:

a) Proximity
b) Curb location
c) Velocity (of object)
d) Heading and velocity of the bus
e) Pedestrian classification
f) Vehicle classification

The simplified algorithms used are listed below together with the number and percentage of situation they identified as indicated in Table 1.

Many situations can be correctly classified as safe by more than one algorithm:

a) Object on curb → safe; 200 situations, 65%
b) Fixed object located at the side of the bus while bus is going straight → safe; 203 situations, 66%
c) Bus stopped → safe; 64 situations, 21%
d) Sweeping motion of bus does not intersect with fixed object → safe, 20 situations, 7%
e) Pedestrian on the street close to the bus → alert, 1 situation, 0.3%

These simplified algorithms are not able to deal with only 5 situations (1.6%).

C. *Conclusion*

The analysis shows that there are some simplified algorithms, which can reliably determine the severity of the situation. Using these simplified algorithms instead of the full ones will considerably speed up the computation. But it is also clear, that they are not sufficient to do this determination for all situations, in our example 1.6% or 5 in 30 minutes need the full calculation.

The frequency by which certain information is used in one of the algorithms indicates its usefulness. Accordingly finding the location of the curb and determining if an object is fixed while the bus is going straight are very useful information, followed by determining if the bus is stopped. Almost all situations were safe, only one situation warranted an alert. Therefore one cannot make statistically significant claims about the usefulness of information regarding the determination of dangerous situations. Nevertheless it should be mentioned, that curb location and pedestrian classification was used to evaluate this one situation.

IV. Limits on the turning rate of the bus

The turning rate of the bus can be limited by many factors. It is impossible to turn the front wheels beyond a certain point, which limits the turning radius. The centripetal force is limited either by the maximal frictional force between the bus and the street or the force that would turn the bus over. Besides these physical limitations, the bus driver wants to be cautious and not get to close to these limits, as well as provide for a comfortable ride for the passengers.

The velocity v and the turning rate ω of the bus have been recorded. The turning radius r and the centripetal acceleration a can be calculated as:

$$r = v/\omega$$
$$a = v\,\omega$$

Figure 19 shows a scatter plot of the turning rate versus the speed of the bus. The data has been taken at 10 Hz during data recording and the plot represents 1% of the total data, randomly sampled.

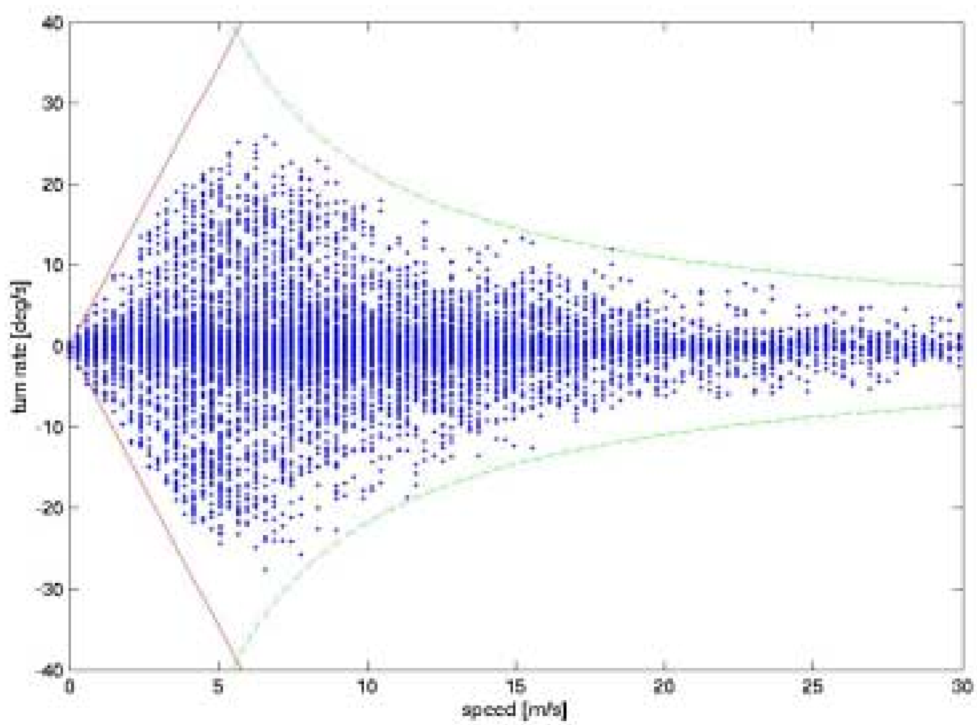


Figure 22 - Turning rate vs. speed. The solid red curves shows the limit imposed by the minimum turning radius and the dashed green curve indicates the maximum centripetal acceleration.

The plot is shown with two enveloping curves, one for the minimum turning radius and the second for the maximum centripetal acceleration.

The minimum turning radius can be inferred from Figure 20[2].

The reference point of all kinematic quantities in the bus is the middle of the rear axis. The minimum turning radius is then:

$$r_{min}=27.25'=8.3\text{m}$$

[2] Measurements taken from "A policy on geometric design of highways and streets", 1984, American Association of State Highway and Transportation Officials, p 21 ff

This value is shown as two solid red horizontal lines in Figure 21 and is a good lower bound for the shown data. There are a few outlier points at very low speed which indicate radii less than r_{min}. They are within the statistical error, they are the ratio of two very small numbers, each having some measurement error.

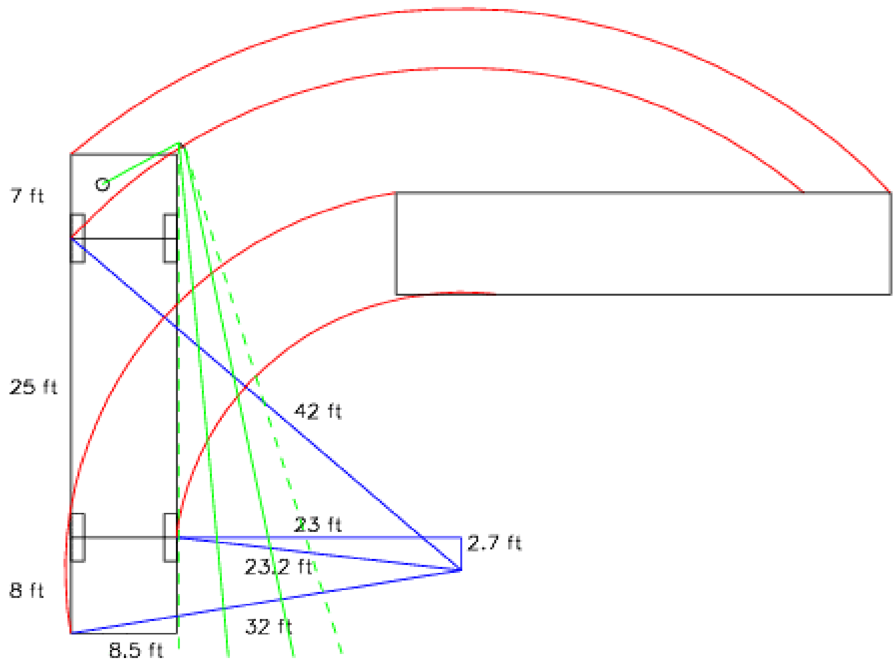


Figure 23 - Kinematic reference points for turning bus.

The limit of the centripetal acceleration due to the maximum friction between bus and street is the product of the acceleration due to gravity and the coefficient of friction. The coefficient of friction is very dependent on the condition of the road, here we take it for good road conditions:

$$a_f = g\,\eta = 9.8\ \text{m/s}^2\ 0.9 = 8.82\ \text{m/s}^2$$

The maximum value of a observed in our data is much less than a_f (see Figure 22). This is not surprising, since it would be dangerous and uncomfortable for the passengers. The maximum centripetal acceleration observed (a_m) is indicated as a solid red line in Figure 22 and the corresponding curves are plotted in the other figures.

The two limits of minimum turning radius and maximum centripetal acceleration form a fairly good envelope for the data. But there is a noticeable blank area around 6 m/s and high absolute turn rates. This might be explained by the effort and time it takes to turn the steering wheel all the way to the limit.

It should also be mentioned, that there is a slight difference in the data distribution between positive and negative turning radii.

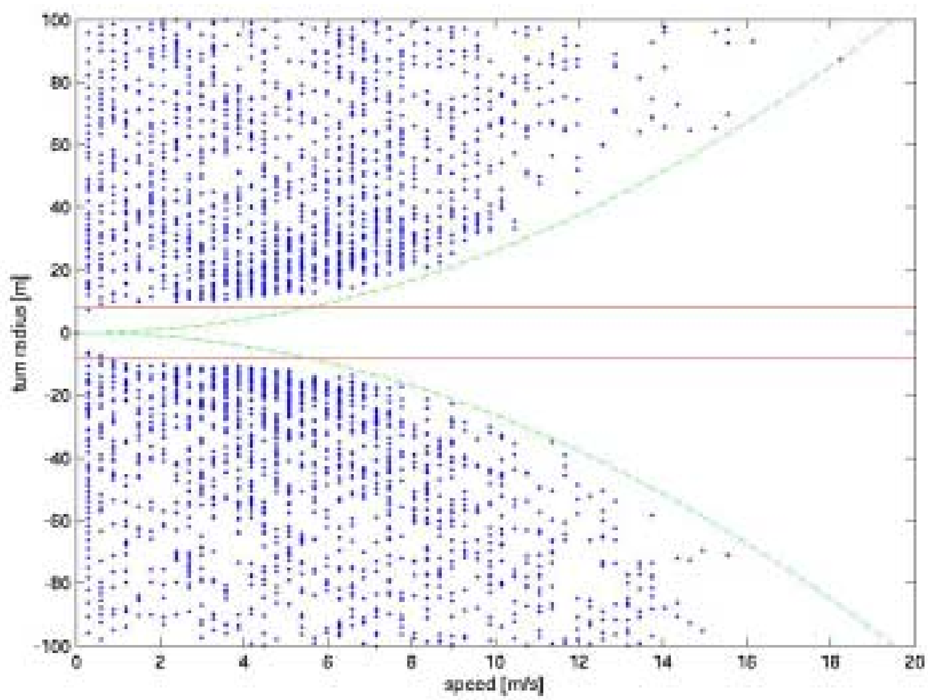


Figure 24 - Turning radius vs. speed. The solid red lines show the limit imposed by the minimum turning radius and the dashed green curve indicates the maximum centripetal acceleration.

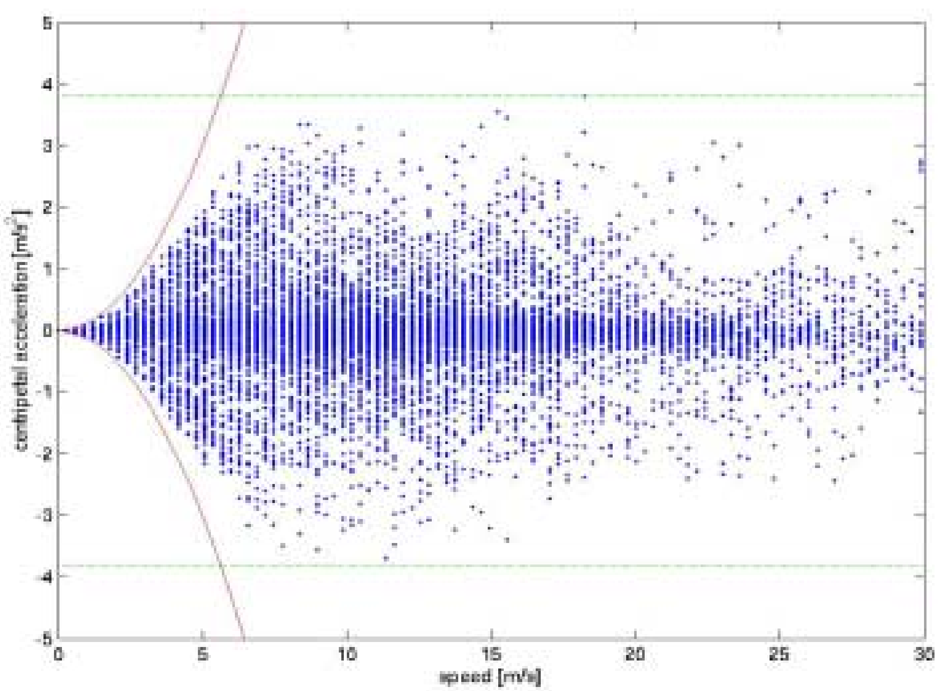


Figure 25 - Centripetal acceleration vs. speed. The solid red curves shows the limit imposed by the minimum turning radius and the dashed green lines indicate the maximum centripetal acceleration.

Appendix E - Cost Benefit Analysis

Cost benefit analysis is a critical element of any technological development focused on safety improvements. It is also challenging as the analysis can be conducted from different points of view and requires many assumptions.

This appendix presents a cost benefit analysis based on a break-even analysis of social costs. Sensitivity analysis is used to explore the impact of changes in the assumptions. The appendix is organized as follows. The first section provides some background on cost benefit analysis. Then the general approach is outlined. Subsequent sections describe data sources and assumptions. Finally the results of the analysis are presented.

I. Background

To analyze the costs and benefits of a technology such as a side collision warning system for transit buses we have to identify a point of view for the analysis, a planning horizon, and a discount rate. Theses terms are defined as follows [Hendrickson and Wohl, 1984]:

- Point of view determines which factors or costs and benefits are included in an analysis. While some [Grant 1982, Kuhn, 1962] argue that public agencies should take the national economic viewpoint, [Hendrickson and Wohl, 1984] argue that feasibility should be considered "from the point of view of those whose funds or resources are being risked. " In this case this is society as a whole, as safety is addressed. However, investment by the private sector in system development, marketing and production can be evaluated be the point of view of whether investment in the technology is worthwhile to a specific individual firm. Our analysis will be based on a social welfare point of view.
- Planning horizon or analysis period defines the period of time over which we are willing to consider investments in or impacts of a project. When considering equipment, it is common to use the physical life or time to replacement as the planning horizon or analysis period. In our analysis, we will use 3 years.
- Interest rate, discount rate, and opportunity costs of capital or minimum attractive rate of return reflects the interest that could be earned from alternative investments. The interest rate reflects the time value of money. The real interest rate differs from the market rate, as it does not include the effects of inflation. While there is much debate, for example, see (de Neufville, 1994) or (Gramlich, 1990), over what rate should be used, the Office of Management and Budget currently recommends a rate of around 2%. Cost of capital represents the real cost to borrow money. This cost will vary with the point of view used for analysis and the source of the money. This value differs from the real interest rate as it reflects the rate at which money is borrowed rather than the returns from alternative investments. Financing will not be addressed in this analysis.

In evaluating and assessing measures of effectiveness, costs, benefits and tradeoffs, there are also several areas of confusion where different users of the term, use the term in a different context. These are briefly discussed in the following points:

- Relative vs. absolute. Relative measures are defined in terms of a comparison to some known technology. In this case our analysis is relative to a transit system without SCWS installed on its buses.

- Quantifiable vs. non-quantifiable measures, attributes, costs and benefits. Quantifiable amounts have a numerical value attached to them so that the magnitude of the numerical value becomes a basis for comparison between alternatives. For example, number of accidents per year. Non-quantifiable amounts are defined in qualitative terms such as large or small and are often more difficult to defend. For example, disruption of traffic due to accidents or aggravation to bus drivers from nuisance alarms is difficult to quantify.
- Monetary vs. non-monetary costs and benefits. The monetarization of costs and benefits by assigning a dollar value to quantified impacts is a subject of frequent debate. Estimating the value of a life is a way of converting non-monetary costs to monetary costs. Other quantities such as urban sprawl or loss of neighborhood integrity represent a significant challenge.

A cost benefit analysis will not give all the answers, but it can help to quantify the social interest and go beyond a market analysis. (Lave, 1996) However, analysts should be aware of the limitations of this tool (Lave, 1996, Dorfman, 1996). It should be noted, that a benefit - cost analysis will not give the final decision: it is only an input to the decision making process. No data speak for themselves. Sensitivity analysis and carefully drawn conclusions will help decision makers, but will not determine the specific system.

II. Approach

Given the challenges facing a cost benefit evaluation of any technology, it is difficult to conduct a definitive cost benefit analysis for a side collision warning system for transit buses. It is also difficult to estimate the cost to develop and bring to market the system, the expected life of the system and most importantly the effectiveness of the system. Furthermore, there is considerable debate in the literature on the cost of accidents (for example, see Broder, 1990, Price, 2000). Given these limitations we explore the costs and benefits of a side collision warning system using a break-even analysis. We determine the cost of a side collision warning system to be equal to the benefits derived form the system.

Such an analysis of the break-even cost of a side collision warning system is useful as it provides an indication of whether or not such a system may be feasible. The analysis presented here for transit buses is based on many assumptions. These include:

- The cost of the SCWS consists of an initial cost and it has a life of three years.
- The only benefits derived from the SCWS are in the form of the comprehensive costs of motor vehicle crashes eliminated and are measured in terms of the social costs of crashes in 2000 dollars (See http://www.nsc.org/lrs/statinfo/estcost0.htm#COST).
- The real discount rate or MARR is 2.1%. (OMB, 1992, OMB, 2002).

The magnitude of the saving is highly dependent on the effectiveness of the system. The performance specifications for the SCWS typically require 95% detection of potentially dangerous situations. However, once a situation has been detected, the driver must recognize and respond. More important than the reliability of detection is the time available for the driver to respond. Eaton manufactures a commercially available SCWS for trucks. The system claims to have produced a 76% reduction in accidents (Kelley, 1999). In this analysis we distinguished between preventing crashes and reducing their severity.

Based on our analysis of bus crash data for Pittsburgh and Washington state (McNeil et al, 1999) and our experience in developing the performance specific for the SCWS for transit buses, we estimate measures of effectiveness. Based on the number of crashes, the number of buses for the transit system, the expected life of the SCWS, we compute the break even cost for a SCWS. This costs includes purchase, installation, and maintenance and service of the system over its life.

III. Data Sources

This analysis requires data from a variety of sources. The following subsection explores these data sources for the cost of crashes, crash frequency, and system effectiveness.

A. *Cost of crashes*

The National Safety Council (NSC) gives following numbers for the economic cost of crashes in 2000 dollars (NSC, 2000):

Death	$1,000,000
Nonfatal Disabling Injury	$ 35,300
Property Damage/Crash (Including non-disabling injuries)	$ 6,500

Or, by injury severity:

Incapacitating injury (A)	$ 47,900
Non-incapacitating injury (B)	$ 16,000
Possible injury (C)	$ 9,100

These costs are economic costs based on wage and productivity losses, medical expenses, administrative expenses, motor vehicle damage, and employer costs for uninsured workers. These economic costs are appropriate for measuring losses due to past crashes. In our situation we also want to account for the value of the quality of life. This is captured by estimated the willingness to pay for improved safety. The comprehensive costs of crashes that is the appropriate value to use in cost-benefit analysis are (NSC, 2000):

Death	$ 3,214,290
Incapacitating Injury	$ 159,449
Non-incapacitating Evident Injury	$ 41,027
Possible Injury	$ 19,528
No Injury	$ 1,861

In reality, the average cost for death and injury is independent of the vehicles involved. However, the average property damage is likely to be dependent on the vehicle type. Buses are bigger and might inflict bigger damage, but at the same time buses drive on average much slower than other vehicles and therefore might inflict less damage. Buses have many more passengers and therefore the amount of lost wages due to lost time is likely to be bigger for buses than other vehicles.

B. *Number of crashes*

In order to estimate the benefits derived from reducing the number and severity of crashing using a SCWS, we explore different sources for the number and severity of crashes involving buses. This analysis is complicated as different data sources use slightly different definitions of the severity of a crash and we need to develop estimates that are consistent with the classification system used to estimate the cost of crashes. Our detailed analysis of the PAT and Washington State (McNeil et al, 1999) with some additional assumptions appears to be the most useful.

Table 2 summarizes the steps used to move from the raw data to the estimate used for this analysis for PAT and Table 3 presents similar data for Washington state. Where data were unavailable assumptions were made. For example the distribution of vehicle crashes between capacitating and non-incapacitating injuries is the same for pedestrians and vehicles. While this is not a realistic assumption it provides a starting point. There are some important differences between the data sets. For example, the PAT data covers 27 months, whereas the Washington state data covers 6 years.

Table 4 shows a more detailed analysis of sample data for PAT. The “total” column in Tables 2 and 3 are consistent with the sample.

Observed Category	Observations From Table 6.3 (McNeil et al 1999)	Number per year	Distribution From FARS & GES (Preusser, 1997)	Distribution From Florida (Preusser, 1997)	Distribution from average of FARS&GES and Florida	Number per year	Categories of Crashes	Total
Pedestrian - fatality	1	0.44	5.70	6.50		0.44	Pedestrian - fatality	7.97%
Pedestrian - injury	55	24.44	22.80	27.00	0.41	10.12	Pedestrian - incapacitating injury	
			31.70	38.80	0.59	14.33	Pedestrian – non-incapacitating injury evident	
Pedestrian - possible injury	85	37.78	39.70	27.70		37.78	Pedestrian - possible injury	
Vehicle collision - fatality	1	0.44				0.44	Vehicle collision - fatality	90.11%
Vehicle - injury	100	44.44			0.27	11.80	Vehicle - incapacitating injury	
					0.38	16.70	Vehicle – non-incapacitating injury evident	
					0.36	15.95	Vehicle - possible injury	
Vehicle collision - PDO	1494	664.00				664.00	Vehicle collision - PDO	
Fixed object - PDO	34	15.11				15.11	Fixed object - PDO	1.92%

Table 2 - Number of Crashes Based on PAT Data

Observed Category	Source	Observations	Number per year	Distribution from FARS & GES (Preusser, 1997)	Distribution from Florida (Preusser, 1997)	Distribution from average of FARS&GES and Florida	Number per year	Categories of Crashes	Total
Pedestrian - fatality	1	9	1.50	5.70	6.50		1.50	Pedestrian - fatality	0.73%
Pedestrian - injury	2	24	4.00	22.80	27.00	0.41	1.66	Pedestrian - incapacitating injury	
				31.70	38.80	0.59	2.34	Pedestrian – non-incapacitating injury evident	
Pedestrian - possible injury	3	0	0.00	39.70	27.70		0.00	Pedestrian - possible injury	
Vehicle collision - fatality	4	15	2.50				2.50	Vehicle collision - fatality	97.67%
Vehicle - injury	5	96	16.00			0.41	18.40	Vehicle - incapacitating injury	
						0.59	26.05	Vehicle – non-incapacitating injury evident	
Vehicle - possible injury	6	2083	347.17				347.17	Vehicle - possible injury	
Vehicle collision - PDO	7	2024.31	337.39				337.39	Vehicle collision - PDO	
Fixed object - PDO	8	71.577	11.93				11.93	Fixed object - PDO	1.59%

Table 3 - Washington State Data

Source of Observations (McNeil et al, 1999)
1 Table 5-4 (Pedestrians and Cyclists)
2 Table 5-5 (Pedestrians and Cyclists)
3 Table 5-6
4 Table 5-4 (excluding Objects, Pedestrians and Cyclists)
5 Table 5-5 (excluding Objects, Pedestrians and Cyclists)
6 Table 5-6 (excluding Objects, Pedestrians and Cyclists)
7 Table 5-2 and Table 5.9
8 Table 5-2 and Table 5.9

Object Involved in Collision with Bus	Population[3]	Sample Source	Functional Goal	Sample Distribution	Potential Impact
Pedestrian	7.2%	70 unique records recorded as "Bus & Pedestrian" extracted from the PAT claim database for the period January 1997 to May 1999.	Pedestrians in the path of bus	21.4%	80%
			Stopped bus, prior to starting motion for pedestrians	17.1%	92%
			Pedestrians in blind spots	15.7%	91%
			Pedestrians in cross walk ahead of turning bus.	10.0%	100%
			Pedestrians under bus	NA	NA
			Pedestrian related events	NA	NA
			Pedestrians in danger	NA	NA
Vehicle	90.2%	93 unique records representing a 30% sample of incidents in the period January 1, 1999 to May 6, 1999 recorded as "Bus & Vehicle"	Inadequate clearance for oncoming vehicles	6.5%	50%
			Sideswiping parked car	9.7%	89%
			Lane change/ merge	47.3%	68%
			Vehicle relate incidents	NA	NA
Cyclist	0.7%	7 unique records recorded as "Bus & Pedestrian" extracted from the PAT claim database for the period January 1997 to May 1999 and identified as involving a cyclist	Cyclists going past bus	100%	29%
Fixed Object	1.9%	Detailed data not available. Distributions and impacts based on judgment.	Fixed objects in the vicinity of the bus	33%	50%
			Fixed objects in blind spots	33%	50%

Table 4 - Qualitative Assessment of Impacts on Functional Goals on Collisions

[3] PAT Claims – January 1997- May 1999

C. *System Effectiveness*

A qualitative assessment based on the expert judgment of the research team suggests that a significant proportion of the bus collisions would indeed be reduced or eliminated if these functional goals are met. Using the PAT database of claims and sampled records to provide more detailed incident report data, we identified the proportion of incidents related to each of the functional goals and then the proportion of these incidents that **may** be impacted by the use of a SCWS as shown in Table 4. For example, 7.2% of incidents involve pedestrians, just over 17% of these incidents occur when the bus is starting from a stopped position, and 92% of these incidents may be positively impacted if the bus had a SCWS. This assessment using the PAT data is summarized in Table 4. Overall, around 42% and 68% of all incidents **may** be positively impacted by the use of a SCWS. These numbers are derived using the data in Table 5 for PAT data and Table 6 for Washington State data. The first two columns of the table provide an upper and low bound for the proportion of bus related incidents that are impacted by a SCWS. The overall effectiveness of 95% is derived from the performance specification that says there will be no more that 5% false negatives. The preventability is derived from the data presented in Table 4 (a weighted average of the estimates). The best and worst cases are the maximum and minimum values of the product of:

- The proportion of crashes that are side collisions
- The proportion of crashes that the system addresses (overall effectiveness)
- The proportion of crashes that are or maybe preventable.

This assessment should be considered to be an upper bound and lower bound on the effectiveness of side collision warning systems for transit buses, although we have not included the value of notification and recording of incidents in reducing fraudulent claims. This is consistent with NHTSA's 1996 estimate of 47% of lane change/ merge crashes avoided using a LCM CAS (IVI, 1996).

We also used some detailed data analysis to derive the values. Based on an analysis of fifty-one bus-pedestrian accidents in Pittsburgh we were able to explore the chances of preventing crashes. Using both crash reports and witness reports, and looking at the chain of events it was judged if a warning system might have been able to prevent the incident. An incident was deemed preventable if there was enough time between identifiable event and collision to avoid or mitigate the collision. If the driver was already aware of the situation the incident was judged not preventable by a CWS. The assessment of whether or not incidents are preventable is summarized in Table 7. The reasons for the not being preventable or maybe being preventable are listed in Table 8. The most significant reason is that the event (possibly) happened too fast to be prevented.

Finally, we distribute the effectiveness between eliminating the crash and reducing the severity of the crash. This is done on the basis of the proportion of crashes that are preventable (~1/3) and the proportion that may be preventable (~2/3).

Categories of Crashes	Side collision From (McNeil et al, 1999) Table 6.5	Side collision Table 1	Overall Effectiveness from Specification	Preventability	Effectiveness Best Case	Effectiveness Worst Case
Pedestrian - fatality	0.81	0.64	0.95	0.89	0.68	0.54
Pedestrian - incapacitating injury	0.81	0.64	0.95	0.89	0.68	0.54
Ped - nonincapacitating injury evident	0.81	0.64	0.95	0.89	0.68	0.54
Pedestrian - possible injury	0.81	0.64	0.95	0.89	0.68	0.54
Vehicle collision - fatality	0.90	0.64	0.95	0.69	0.59	0.42
Vehicle - incapacitating injury	0.90	0.64	0.95	0.69	0.59	0.42
Veh - nonincapacitating injury evident	0.90	0.64	0.95	0.69	0.59	0.42
Vehicle - possible injury	0.90	0.64	0.95	0.69	0.59	0.42
Vehicle collision - PDO	0.90	0.64	0.95	0.69	0.59	0.42
Fixed object - PDO	0.67	0.33	0.95	0.50	0.32	0.16

Table 5 - Effectiveness Based on PAT Data

Categories of Crashes	Side collision From (McNeil et al, 1999) Table 6.5	Side collision Table 1	Overall Effectiveness from Specification	Preventability	Effectiveness Best Case	Effectiveness Worst Case
Pedestrian - fatality	0.75	0.64	0.95	0.89	0.63	0.54
Pedestrian - incapacitating injury	0.75	0.64	0.95	0.89	0.63	0.54
Ped - nonincapacitating injury evident	0.75	0.64	0.95	0.89	0.63	0.54
Pedestrian - possible injury	0.75	0.64	0.95	0.89	0.63	0.54
Vehicle collision - fatality	0.75	0.64	0.95	0.69	0.49	0.42
Vehicle - incapacitating injury	0.75	0.64	0.95	0.69	0.49	0.42
Veh - nonincapacitating injury evident	0.75	0.64	0.95	0.69	0.49	0.42
Vehicle - possible injury	0.75	0.64	0.95	0.69	0.49	0.42
Vehicle collision - PDO	0.75	0.64	0.95	0.69	0.49	0.42
Fixed object - PDO	0.75	0.33	0.95	0.50	0.36	0.16

Table 6 - Effectiveness Based on Washington State Data

Preventability	Number	%
Preventable	13	25.5
Maybe preventable	26	51.0
Not preventable	12	23.5

Table 7 - Preventability of bus-pedestrian incidents

	Reason	Number	%
Not preventable	Driver was aware of situation	4	7.8
	Person stepped suddenly in front of bus	2	3.9
	Vandalism	2	3.9
	Fraudulent claim	1	2.0
	Pedestrian fell/was pushed before collision	3	5.9
Maybe preventable	Maybe too sudden	22	43.1
	Driver saw person	3	5.9
	Not enough information	1	2.0

Table 8 - Reason for not/maybe being preventable

IV. Analysis Assumptions

As discussed, the analysis requires several assumptions. These assumptions are reiterated here:

- Constant Dollars and Time Value of Money

Current dollars refers to the value of the dollar in the year in which it is spent. Constant dollars refers to the purchasing power of a dollar in some specified year. In converting from current to constant dollars care must be taken to use a factor that reflects inflation rather than time value of money. The terms current and constant dollars are not intended to represent a present, past or future value of monetary investment or revenue, but the purchasing power of a dollar in that particular year. There is considerable debate over how these conversions are actually done. It seems likely that the value of a life should inflate at the same rate as the general rate of inflation, but injury costs may inflate at the rate of medical care costs, which generally is higher than inflation. Cost indices (the most commonly known is the consumer price index) are aggregate value that reflects purchasing power of a basket of "goods and services."

The basic relationship holds

$$\$\$_{\text{year } t} = \$\$_{\text{year } T} * CI_{\text{year } t} / CI_{\text{year } T}$$

where

$\$\$_{\text{year } t}$ = value in year t

$\$\$_{\text{year } T}$ = value in year T

$CI_{\text{year } t}$ = cost index in year t

$CI_{\text{year } T}$ = cost index in year T

- Life of a system

The life of the system is assumed to be 3 years.

- Value of notification

In our analysis of crash data, the ability to notify the drive that an incident has occurred has some value. This is not directly accounted for in this analysis.

- Social versus agency costs

The costs benefit analysis focuses on social costs rather than agency costs.

V. Analysis Results

A. *Cost benefit analysis*

Table 9 summarizes the values **assumed** for savings from prevention and reduction in severity for each of the various types of crashes, and the effectiveness in reducing crashes for PAT. These values are then used with the approximate annual number of crashes for PAT to produce total savings for each type of incident. Therefore, the crash savings to society (because we have used a social cost of crashes) are almost $4 million per year. PAT has approximately 900 buses, if each bus were fitted with a SCWS and the system had a life of 3 years, the system would cost under $12,500 to break even. We believe that it is feasible to develop, manufacture, install and maintain a system for under this amount. Therefore, with relatively modest reductions in incidents significant benefits can be gained.

Type of Incident	Savings		Effectiveness		Annual # of Crashes	Total Savings
	Prevented	Reduced	Prevented	Reduced		
Pedestrian - fatality	$3,214,290	$3,054,841	0.18	0.36	0.44	$749,814
Ped - incapacitating injury	$159,449	$118,422	0.18	0.36	10.12	$725,597
Ped – nonincapacitating injury evident	$41,027	$21,499	0.18	0.36	14.33	$217,795
Pedestrian - possible injury	$19,528	$17,667	0.18	0.36	37.78	$375,010
Vehicle collision - fatality	$3,214,290	$3,054,841	0.14	0.28	0.44	$578,012
Veh - incapacitating injury	$159,449	$118,422	0.14	0.28	11.80	$652,019
Veh - nonincapacitating injury evident	$41,027	$21,499	0.14	0.28	16.70	$195,722
Vehicle - possible injury	$19,528	$17,667	0.14	0.28	15.95	$122,045
Vehicle collision - PDO	$1,861	$931	0.14	0.28	664.00	$344,717
Fixed object - PDO	$1,861	$931	0.05	0.10	15.11	$2,939
						$3,963,670

Table 9 - Hypothesized Worst Case Savings by Incident Type for Side Collision Warning Systems For PAT

Our assessment of effectiveness is very conservative but recognizes that we found approximately 25% of pedestrian incidents were not preventable and approximately 50% may not be preventable. Combined with a system effectiveness of 95% we have assumed that 30% of vehicle incidents are positively impacted by the SCWS system and 20% of pedestrian incidents. This analysis could be considered to provide a lower bound. That is, from a social welfare point of view, it is worth spending **at least** $5,000 on a SCWS for a transit bus.

We repeated that analysis for a best-case scenario in which the system is more effective in both preventing crashes and reducing the severity of the crash. We also repeated the analysis using the Washington State data. The results are summarized in Table 10. The Washington state data uses an estimated number of buses for Washington State of 1658 derived from the APTA performance indicator statistics for 2000. These are derived from the National Transit Database (FTA, 2001).

Case	Effectiveness		PAT		Washington	
	Pedestrian	Vehicle	Cost Savings	Break Even Cost	Cost Savings	Break Even Cost
Worst	0.18	0.14	$3,963,670	$12,676	$10,092,650	$17,521
Best	0.23	0.2	$5,289,642	$16,917	$11,888,407	$20,638

Table 10 - Sensitivity Analysis

B. *Value of Notification and Recording*

In many cases, the bus driver leaves the scene of the collision or is unaware that a collision has occurred. We suspect that in most of these cases the bus driver did not notice the event:

- The bus driver left the scene ("hit and run") in 12% of pedestrian, 7% of cyclist, 4% of object, 3% of car and 1% of truck collisions. The significant higher rates of "hit-and-run" in the pedestrian collisions are expected if they are unintentional, because of the smaller physical impact.
- The number of bus-pedestrian cases where the driver claims to have no knowledge of the incidents is about the same as the number of cases where the driver did not notice the collision itself, instead was notified by a passenger or pedestrian. This fact suggests, that many of the "hit-and-run" cases are indeed unintentional. The number of bus-vehicle incidents in which the driver was unaware of the incident was approximately 22% for the PAT data. This is significantly higher than for the Washington State data

In some cases the event may never have actually occurred. Analysis of the PAT data suggests that over 7% of claims are due to vandalism or fraudulent claims. The sensor system provides a way of recording this data to support the drivers' statements that the incident did not occur.

C. *Value of Claims Analysis*

In reality very few claims have been settled. Table 11 shows some summary statistics for the number and average amount of claims that have been paid or settled. Although the samples are small, a comparison of "Bodily Injury" claims that have been settled for "Bus & motor vehicle" and "Bus & pedestrian" accidents seemed to warrant further investigation. The average claim was the order of $3,000 for both types of incidents and there were 27 and 13 claims respectively. This suggests that while in aggregate there are many more "Bus & motor vehicle" claims than "Bus & pedestrian" (1594 versus 140 claims) the impact of injuries in "Bus & pedestrian" incidents is far more significant than the number of incidents suggests and pedestrian incidents should not be ignored. Figure 23 shows a histogram of the relative frequency of the value of settlements for bodily injury claims for each type of accident.

Type	Code	Bus & fixed object		Bus & motor vehicle		Bus & pedestrian	
		Number	Average Claim	Number	Average Claim	Number	Average Claim
PAID	NA			1	$687.13		
PAID	C/R			155	$1,138.15		
PAID	PD-1			2	$617.17		
SETTLED	NA					1	$8,500.00
SETTLED	BI			27	$3,023.57	13	$2,671.62
SETTLED	PD-1			455	$878.82		
SETTLED	PD-2	19	$809.92				
Total		19		640		14	

Table 11 - Claims Paid or Settled

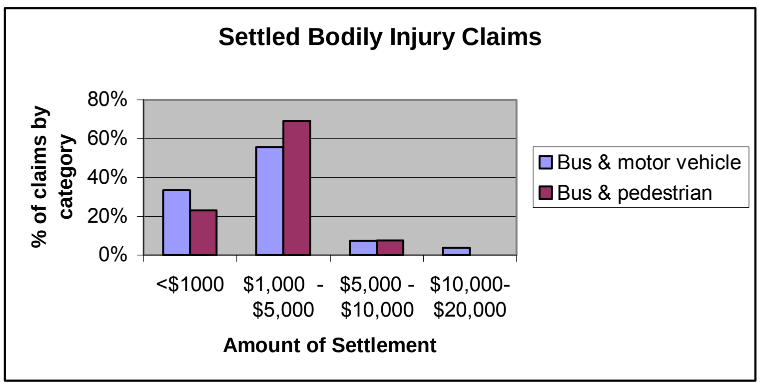


Figure 26 - Bodily Injury Settlements

VI. Conclusion

An analysis of crash data from Pittsburgh and Washington state, an assessment of opportunities for preventing or eliminating side collision for transit buses has demonstrated that the savings in the social costs of accidents will be recouped if the costs of development, production, installation and maintenance of a SCWS is less than $12,000 and the system last at least 3 years. Additional saving can be realized by accounting for fraudulent claims, and reduced driver stress.

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Appendix F - Alternate Organization of Specifications

An alternate way of organizing the Performance Specifications for a transit bus would be to base it on what things need to be known and the ways of knowing them. This is summarized in the following chart. The bolded items with cross references to a specification number are items which are included in the baseline configuration for an SCWS. The items not bolded with cross references to a specification number are items which are included in enhanced or will be included in a future SCWS Specification as the technology matures. The items not in bold and without cross references have not been incorporated in this specification, but represent opportunities for vendors to enhance their systems to include other ways to modify the probability calculation (See Appendix A.III.D).

		Things to Know		
		Bus State	Objects	Environment
Ways of Knowing	Preloaded	Minimum turning radius Kinematic properties of the bus Maximum speed Maximum acceleration Min-max weight Power of the engines Max. braking power **Blind spots – III.C** Driver model: Reaction time Max speed of turning the front wheel	Map based fixed objects Same/similar to bus state, but relating to vehicles, or pedestrian, or others Shapes of vehicles **Object class – IV.E.1,2,3** **Pedestrians in front of wheel – IV.F**	Map based intersections and turns III.E.1,2 Map based routes and bus stops – III.E.3 3-D intersection environment model – III.E.1 Shapes of buildings, fixed objects, curbs
	Sensed Internally	**Speed – I.A.1** Weight Slope **Yaw rate – I.A.2** Acceleration – I.A.3 **Doors open / closed – II.A.1** **Turn signals on / off – II.A.2,3** **Hazard lights on / off – II.A.4** Front wheel position – II.A.7 Gear Gas pedal position – II.A.6 Brake pedal position – II.A.5 Engine status		Time – III.E.5 Direction of travel – III.E.4
	Sensed Externally	GPS position – III.D Position relative to landmarks – III.D	**Object positions – IV.A,B,C,D,G** **Object velocities** – **IV.H,I** Object yaw rates – IV.J Shape of object Color of object Reflectivity of object	Temporary occlusions – III.F Sensed local objects **Curb location – III.A,B** Outside conditions: rain, snow temperature, etc. Road condition

Table 12 - Alternate organization of performance specifications

Appendix G - Glossary of Terms

Detect – to infer the presence of an object from raw sensor output data

Determine – to apply an algorithm to input data to arrive at a result

False alarm - the SCWS gives an incorrect alarm

Know – to have predetermined data and loaded it into the computer

Measure – to take sensor data and calculate a physical quantity from it

Nuisance Alarm - the SCWS gives the correct alarm, but the alarm is considered unhelpful and a nuisance by the driver

Optional – These are specifications that would enhance the performance of a SCWS, but are not considered part of the baseline system due to their expense or lack of commercialization in the near term. They could be added as they become more readily available.

Safety Level – The definition for SCWS safety levels are broken into five categories.
1. **Aware:** Baseline Situational Awareness. The transit operator and pedestrian see strictly non intrusive indications be they bumper stickers, running lights, video or the lack of any active alerts, warnings, evasions, or notifications.
2. **Alert:** Potential Obstacles. Alerts are semi-intrusive information such as enhanced video indicating potential obstacles, lights indicating the close proximity of an obstacle, or a pleasant voice alerting a pedestrian to the presence of a moving bus.
3. **Warn:** High Likelihood of Collision. Warnings span the spectrum from intrusive information such as voice or melodic sounds to intrusive interference such as shaking the steering wheel and or seat, vibrating the brakes, or a loud buzzer all indicating a high likelihood of collision.
4. **Evade:** Imminent Collision. Evasive actions include active control of the transit bus such as steering or applying the brakes. The Evade safety level has not been included in the specifications since it is not considered an option for the near term SCWS.
5. **Notify:** Collision has occurred. Notification involves informing the transit operator through an intrusive light or voice that a collision has occurred and data (either computer and/or video) has been saved.