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# Developing an Adaptive Warning System for Backing Crashes in Different Types of Backing Scenarios

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*Young children are overrepresented in run-over backing crashes. The research goal was to propose a backing warning system based upon drivers' backing behavior that was sensitive to different backing scenarios. A backing collision avoidance model that is sensitive to different backing scenarios needs to consider how drivers accelerate and respond to unanticipated hazards while backing. To develop a backing warning system that supplements the abilities of a driver, the driver's response times and backing acceleration were recorded in a field experiment in two different backing scenarios (short backing, e.g., a parking lot, and long backing, e.g., a driveway). The results show that those backing a long distance reached greater peak velocities than those backing short distances. Drivers traveling at greater speeds require greater warning distances than are offered by current backing sensor systems. Additionally, driver brake reaction times and braking latency times were much longer when backing than is typical when responding to hazards and driving forward. From the findings, a backing warning algorithm is proposed that may be optimized for short and long backing scenarios based upon the brake reaction times, braking latencies, peak speeds, and acceleration behaviors of the short and long backers, respectively.*

**Keywords** backing camera, backing crashes, driver behavior

## 1. Introduction

Young children are overrepresented in backing crashes (Fenton, Scaife, Meyers, Hansen, & Firth, 2005). High-profile vehicles, like SUVs and minivans, are known for their use by

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families with young children (Brison, Wicklund, & Mueller, 1988; Fenton et al., 2005). A potential problem is that high-profile vehicles have limited rearward views and are overrepresented in backing crashes (Centers for Disease Control and Prevention [CDC], 2005; Consumer Reports, 2005; Fenton et al., 2005; Paine & Henderson, 2001). As expected, back-over crashes involving young children increase when you mix young families with vehicles that have limited visibility toward the rear (Agran, Winn, & Anderson, 1994; Fenton et al., 2005; Murphy, White, & Morreau, 2002; Patrick, Bensard, Moore, Partington, & Karrer, 1998). As a means of addressing backing safety, drivers' responses and backing accelerations were recorded in a field experiment. The experiment was conducted to gain information for the development of a backing warning system for short backing (SB) and long backing (LB) scenarios. Current backing warning systems are developed only for SB scenarios.

## 2. Background

A primary goal of most transportation safety–related research is to improve crash avoidability. To determine if a crash is avoidable once a threat is detected, three elements must be known (see Table 1 for a definition of terms).

1. The distance to contact (R),
2. The distance the vehicle will travel during the response time for that scenario (or optimal percentile brake reaction time)($D_{RT}$) and
3. The stopping distance (Ds).

If we know the above quantities, then the vehicle can stop if the expression on the lefthand side of the inequality in Equation 1 is positive:

$$R - D_{RT} - D_S > 0 \tag{1}$$

If Equation 1 is not true, warning distance (WD) $= D_S + D_{RT}$ (warn immediately). If true, continue to monitor.

We want to design a warning system such that the above quantity is (almost) always positive. We can only influence the range the system will monitor. Adjusting the monitoring range appropriately takes some skill. First, one has to decide what is the most suitable range for SB and LB scenarios. Second, because the driver does not indicate to the warning system in which scenario he or she is currently backing, one must identify from velocity and/or acceleration information a prediction of which backing scenario is currently the operative one and use the appropriate range. Ideally, it would be best if the system were able to predict whether the driver were planning to back a longer distance (at a presumably greater velocity), or a shorter distance (at a presumably lower velocity). WD is set to a distance that is a minimum of the final velocity ($V_f$) or the peak velocity (Vpeak).

### *2.1. Distance to Contact (Detection Range) to the Rear (R)*

Current backing sensor systems monitor a range of fewer than 2 m (approximately 6 ft). After measuring several vehicles types, one study indicated that a 0.6 m object could not be seen any closer than 4.5 m to 9 m (15 to 30 ft) from the rear of most station wagons and SUVs (Paine & Henderson, 2001). Consumer Reports (2005) measured the blind spots of several vehicle types and reported the average blind spot for a sedan to be from 3 to 10.7 m

**Table 1**
Definition of Terms

| Term | Abbrev | Description |
|---|---|---|
| Coefficient of friction | c | The coefficient of friction. |
| Acceleration | A, $\mu$ | A = g × c. A positive number suggests a positive average acceleration. A is measured in m/s/s. $\mu$ is measured in Gs. |
| Brake reaction time | $t_{RT}$ | The time from when a driver has detected an object to when he or she hits the brake or completes a steer (He or she has responded by the vehicle has not). |
| Braking latency | $t_{BL}$ | Sometimes referred to as brake lag, or vehicle latency is the time from when the brake pedal is applied to the point when it actually does respond in an efficient and measureable manner. There are mechanical and cognitive sources for this delay. |
| Deceleration | $\mu_d$ | A negative number suggests negative average acceleration, or deceleration, at which a vehicle can decelerate to a stop (measured in Gs) |
| Distance | D | Distance the vehicle will travel during a time period. Distance during system latency $D_{SL}$, distance during brake reaction time $D_{RT}$, and distance during braking latency $D_{BL}$. |
| Gravity | g | gravity (32.2 ft/s/s or 9.81 m/s/s) |
| Range | R | Distance from the rear of the vehicle to the obstacle at the moment the obstacle is within the sensor's detection threshold. |
| Stopping distance | Ds | The kinematic stopping distance of the vehicle from hard braking to stop. |
| Time | t | The time involved in some component of system or driver response |
| Time in maneuver | $t_m$ | Time from when the driver started backing and to reach the identified velocity. |
| Total distance to stop | TDs | The total distance to stop is equal to the response distance (Drt) plus the stopping distance (Ds) |
| Velocity | V | Velocity (ft/s or m/s). $V_o$ is original velocity and $V_f$ is final velocity (at impact). |
| Warning distance | WD | Distance at which warning is initiated, which should be greater or equal to the total distance to stop (TDs) |
| Warning system latency | $t_{SL}$ | The time for the system to sample the area, find the object, recognize the object as a hazard, and warn the driver (if necessary) |
|  | o | Used as a subscript to denote the original event, at the point the sensor system detects an object within its detection range. |
|  | i | Used as a subscript for one of the n components of response time |
|  | n | Total number of response time components ($T_{SL}$, $T_{RT}$, $T_{BL}$) |
|  | f | Used as a subscript to denote final velocity, the velocity of the vehicle when it reaches the obstacle if there is no driver intervention. |
|  | peak | Peak velocity, the average peak velocity of backers. May refer to the average peak velocity of a short backer or the average peak velocity of a long backer. |

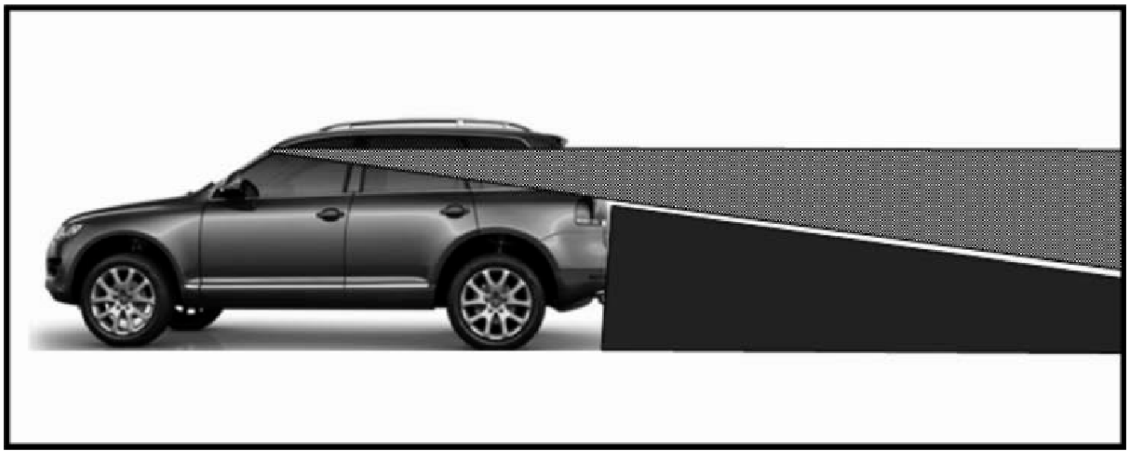

**Figure 1.** The cone of visibility (lighter shaded region) and obscured (darker shaded region) areas behind a high profile vehicle.

(10 to 35 ft), whereas SUVs and pickups had an average blind spot of up to 15.2 m (50 ft) (Figure 1).

### 2.2. *Warning System Latency and Sampling Period ($t_{SL}$)*

To determine how far the vehicle will travel during the overall response time for the scenario ($D_{RT}$), there are three separate reaction time components that must be considered. These three components include the time for the warning system to react, the time for the driver to react, and the time for the vehicle to react. Here we focus on the warning system latency. Warning system latency ($t_{SL}$) should not be confused with braking latency ($t_{BL}$). *Warning system latency* refers to the time necessary for the warning system to sample the environment. The warning system should also filter out anomalous information and offer a warning to the driver (if necessary). Warning system latency has been estimated at 0.2 s (Eberhard, Moffa, Young, & Allen, 1995).

A study by Glazduri (2005) measured the response of several backing sensor systems and reported warning system delays with a range from .08 to .23 s. All warning system latencies ($t_{SL}$) were also reported to be within the recommended limit for low-velocity sensor systems of 0.35 s.

### 2.3. *Driver Reaction Times When Backing ($t_{RT}$)*

When evaluating the response latency, in addition to the system latency ($t_{SL}$) discussed above, one also needs to consider the brake reaction time by the driver ($t_{RT}$) and braking latency ($t_{BL}$) by the driver. The research sometimes reports brake reaction time and braking latency as a single time and sometimes as separate components. Regardless of the methodology of the experimental foundation for the driver's contribution, the time to the brake ($t_{RT}$) and the time from braking to effective deceleration ($t_{BL}$) must be accounted for.

Williams (1999) measured reaction times from an alarm up to measurable deceleration, which includes braking latency ($t_{BL}$) time and time to brake ($t_{RT}$). An average time to measurable deceleration ($t_{RT} + t_{BL}$) near 1.0 s was reported as most probable. The distribution was negatively skewed in such a way that the graph was somewhat triangular shaped between 0.5 and 1.9 s. Williams' results are similar to those of other researchers who included the time from brake application to effective braking in the response time.

Lerner, Harpster, Huey, and Steinberg (1997) reported average reaction times for backers in several situations. Drivers were asked to respond by braking when they heard the backing warning. The drivers backed toward a wall ($t_{RT} = 450$ ms), parallel parked ($t_{RT} = 530$ ms), and responded during an extended curve ($t_{RT} = 630$ ms). Reaction time was measured from the onset of the audible alarm up to brake application ($t_{RT} = 0.45$ to 0.63 s). Therefore, if we assume a 0.25 second braking latency, the results by Lerner et al. ($t_{RT} + t_{BL} = 0.70$ to 0.88 s) become closer to the findings by Williams (1999).

On the basis of the available research, a full response time (a response that includes the time from onset of the warning to 0.4 Gs deceleration (i.e., the sum $t_{RT} + t_{BL}$) to a conspicuous object directly ahead is near 1 s. The coefficient of variation of driver reaction times is near 35% (Hoffman, 1991).

### 2.4. *Vehicle (Braking) Latency ($t_{BL}$)*

Several studies have shown that the variability within the braking latency phase of the driver's response is influenced by driver cognition. One may expect drivers to brake with similar force and velocity regardless of the complexity of the cognitive portion of a response. However, drivers responding to a known stimulus pushed the brake pedal faster and had a higher deceleration than did drivers who were responding to road hazards. Three types of studies have examined this: those that measured braking latency using a light stimulus (Barrett, Kobayashi, & Fox, 1968; Koppa, Fambro, & Zimmer, 1996; Parkes & Hooijmeijer, 2000; Scott, Candler, & Li, 1996), those who measured response latency to a road hazard (Broen & Chiang, 1996; McGehee, Mazzae, & Baldwin, 2000; Otto, Otto, & Overton, 1980; Van Winsum, 1998), and those that measured braking latency to a road hazard while engaged in a cell phone task (Akcelik & Beasley, 2001; Muttart, Fisher, Pollatsek, & Knodler, 2007). The literature shows that braking latencies increase as the cognitive portion of the response increases. A backing warning may be a low-probability event and may require a driver to respond at a time he or she does not see the hazard. Low-probability events and unknown hazards are more complex response scenarios. The braking latencies in the related research report times from 100 ms when responding to the onset of a lamp to near 250 ms when responding to a road hazard and near 400 ms when engaged in a cell phone task. Braking latencies near 250 ms would typically be expected in emergency response situations.

### 2.5. *The Stopping Distance (Ds)*

The minimal stopping distance is a well-known function of the velocity ($V_f$) and deceleration immediately after the driver has responded ($\mu$ is the coefficient of friction):

$$D_S = \frac{V_f^2}{2 \times g \times \mu} \tag{2}$$

We want to know, unfortunately, what is not known, which is what $V_f$ will be when a warning sounds. In the SB scenario, presumably $V_f$ will be smaller than it is in the LB scenario. Much of our research is directed towards identifying $V_f$.

### 2.6. *Current System: Nonadaptive Range (R)*

Looking back at Equation 1, it is clear that the success of a warning system depends on three quantities: the range (R), the response time ($D_{RT}$), and the stopping distance ($D_S$). Ideally the range should be a function of the scenario: SB or LB scenario. Yet this is not the case in all current systems. For example, the test vehicle's backing system, as well as two other vehicle models, were evaluated to determine the detection range of the backing sensor system. None of the test vehicles gave a warning to the driver until within 6 ft of an obstacle. With minor variations, the sensor/warning systems were similar to the vehicle we tested. Figure 2 shows the camera view and the visual warning that was offered at each distance. The warning lights were mounted to the roof of the vehicle over the back window.

The current sensor and warning system provides a fixed range-based warning. An audible beeping and the green, yellow, and red lights offered the driver a warning when closing on an obstacle. Importantly, in the current system, vehicle velocity, acceleration, and driver response times have no effect on when the warning is issued. On the basis of the

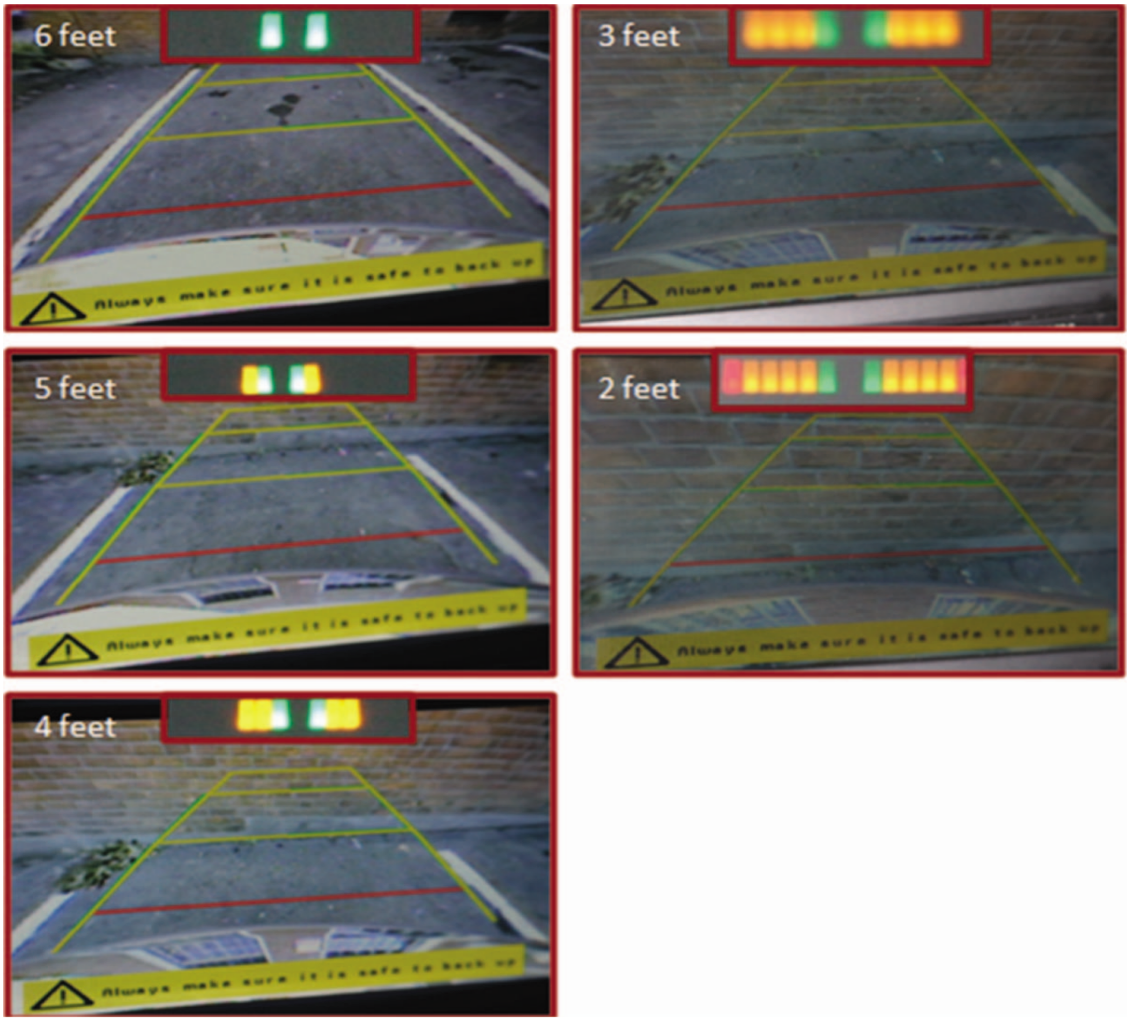

**Figure 2.** Camera views with associated visual warning (inset) at various distances. (Figure provided in color online.)

literature (and assuming an average deceleration rate), drivers traveling a velocity of 3.8 mph or more will not be able to stop before striking the obstacle.

To consider a velocity of 3.8 mph (5.6 ft per s) in context, consider that average walking velocity for those crossing against a DON'T WALK signal is near 6 feet per s (Feng & Wu, 2004). A fixed detection range with no accounting for acceleration, velocity, or driver response time will likely lead to a crash if a vehicle is backing faster than walking velocities. Clearly, an understanding of the velocity and acceleration rates of backers is necessary.

### 2.7. Proposed System: Adaptive Range

There are several better options than using seemingly arbitrary fixed-range detection to trigger a warning. A slight improvement to an arbitrary fixed-range system would be a fixed-range system based upon canonical numbers, such as the 85th percentile velocity and response times. An 85th percentile system involves a fixed range but would be less arbitrary. A still better alternative to a fixed-range warning system would be real-time decisions that consider the present velocity, acceleration, and the anticipated peak velocity of the vehicle in the next few seconds as the vehicle approaches a detected object. Such an adaptive system would decide whether or not to warn and, if to warn, at what range the warning should be issued—that range depending on whether the scenario was a SB or LB scenario. If a warning system detects a reasonably distant obstacle to the rear as the vehicle starts backing, a "no warning" decision will likely be made based upon the present low velocity, minimal acceleration, and distance of the obstacle. However, if the vehicle is traveling at 1 mph and sharply accelerating, a decision to warn the driver may be commanded. If accelerating, an assumption of a constant velocity at the outset of backing will underestimate the likelihood of a crash. An assumption of constant acceleration when near peak acceleration will overestimate the likelihood of a crash.

The concepts for modeling the backing acceleration over time should be similar to those for modeling forward acceleration over time (Bham & Benekohal, 2002; Bonneson, 1992; Long, 2000). Like forward acceleration, backing acceleration should have three phases. In Phase 1, acceleration is slow while the foot moves from brake to throttle and subsequently to a desired throttle displacement. Phase 2 encompasses the time to reach the peak acceleration, and Phase 3 is the linearly decreasing portion of acceleration after the driver reaches the desired peak acceleration. A linear acceleration function will overestimate projected vehicle velocity and distance early in backing and underestimate velocity and distance later in backing if compared to a polynomial function.

### 2.8. Research Goals

The goal of the current research is to propose an adaptive backing warning system that can differentiate between faster (long) backers (e.g., drivers backing down a road or long driveway), and slower (short) backers (e.g., drivers backing out of a parking spot), as early as possible. A system that discerns long backers from short (slower) backers will be better able to anticipate the driver's future velocity (within the detection range). Being able to anticipate a driver's actions will allow for an improved backing warning system that decreases crash rates while minimizing nuisance warnings. The information that is necessary to propose an adaptive warning system includes the peak velocity, brake reaction times, braking latency, and acceleration behaviors of drivers who are unaware of a backing warning system.

## 3. Method

The current study acquired information necessary to develop an adaptive backing warning system. The information included measurement and determination of where the driver is fixating (Hurwitz et al., 2010), backing acceleration for SB and LB maneuvers, brake reaction time to an audible warning ($t_{RT} + t_{BL}$), and crash avoidance probabilities. Brief descriptions of the methods are included here, but additional detail can be found in the Hurwitz et al. article.

Although potentially dangerous situations can be negotiated in a simulated environment, such is not the case in the field. The study goal was to propose a backing warning system based upon drivers' natural backing behavior. To accomplish this goal it was necessary to learn more about backing behavior by replicating long-backing and short-backing scenarios in the field with safety constraints. A short acceleration distance was defined as a backing maneuver less than the length of a vehicle (approximately 5 m or 16 ft), whereas the LB maneuver involved straight backing of approximately 61 m (200 ft). A padded piece of plywood on a hinge the size of a 50th percentile 4-year-old was used as a surrogate for a child behind the vehicle, and tarpaulin stretched over tables replicated parked vehicles (Figure 3).

Drivers backed from a location between two surrogate vehicles and were required to respond to the child surrogate once during a short-backing scenario. The experiment was conducted on a closed parking lot.

### 3.1. Participants

Thirty-six drivers with valid driver's licenses were recruited from the Western Massachusetts area. Participants included 28 males and 8 females with an average age of 27.6 years and 9.3 years of driving experience. No attempt was made to stratify the sample to match the demographics of those who have backed over pedestrians.

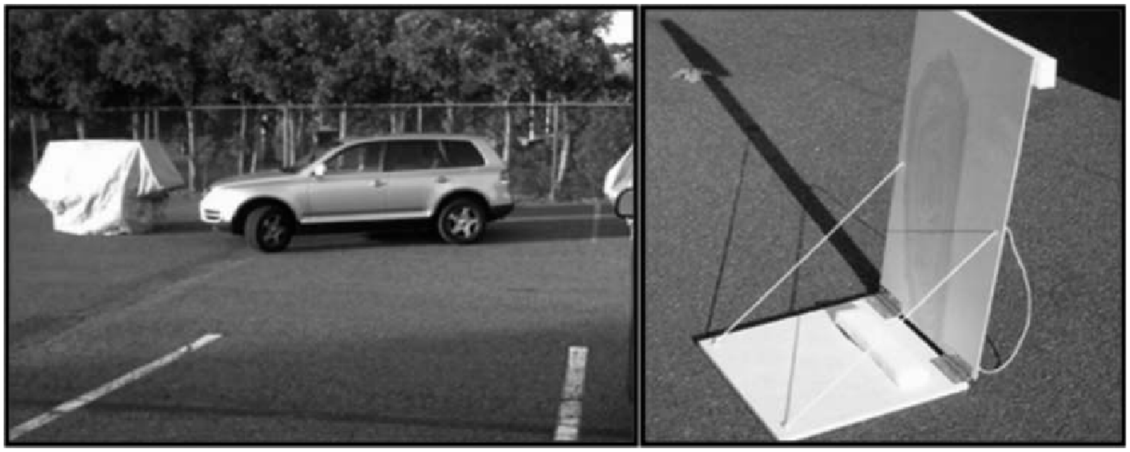

**Figure 3.** Vehicle backing between obstacles (left) and the surrogate obstacle that was the size of a 50th percentile 4-year-old child.

### 3.2. *Equipment*

The test vehicle was a 2007 SUV with a combined rear-view camera and sonar sensor (Figure 4). It was equipped with four rear sensors to detect objects behind the vehicle. There were warning lights on the interior roof at the front and back of the vehicle (Figure 2). The warning lights showed green, amber when within 6 ft of an obstacle, and red when within 2 ft of the obstacle. The audible warning sounded beeps to indicate an obstacle was behind, and as the vehicle moved closer to an object the beep frequency increased. At an approximate 1-foot distance, the beep became continuous.

A Vericom 3000 accelerometer was mounted to the windshield and collected vehicle velocity, engine velocity, and throttle percentage from the vehicle's onboard diagnostic port (OBD II). The Vericom separately recorded vehicle velocity, tri-axle accelerations, and brake pedal displacement.

A hinged flap was attached above the sensor at the rear bumper of the vehicle and could be made to cover the sensor by pulling a string that was attached to a string potentiometer. A pull of the potentiometer was recorded by the Vericom that placed an identifying mark on the data. The Vericom recorded at 100 Hz, whereas the OBD II data was recorded at 7 Hz.

### 3.2. *Procedure*

A researcher familiarized each driver with the vehicle features. These features included the proximity warning and the rearview camera. Participants completed 16 drives (trials), each of which included a series of short- and long-backing maneuvers. The SB maneuvers were similar to backing out of a parking space. In the SB scenarios, the drivers backed

**Figure 4.** The interior of the test vehicle with rear camera view in the center console.

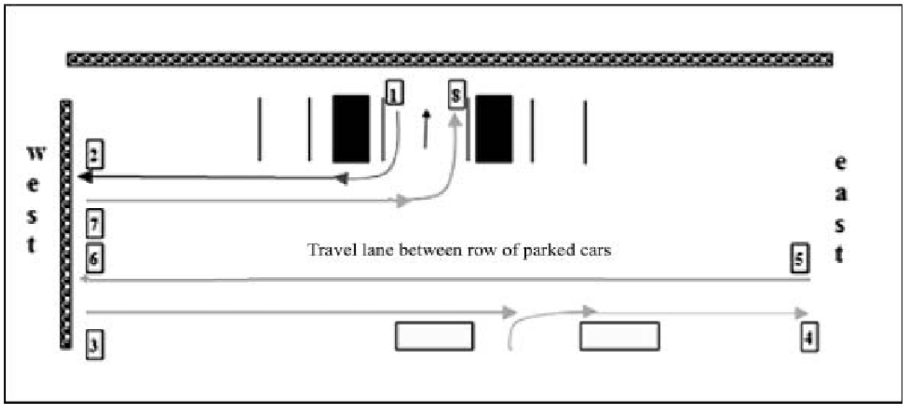

**Figure 5.** Diagram of the sequence of parking maneuvers performed. *Note:* The line from station 1 to station 2 represents the short backing scenario and the line from station 5 to station 6 represents the LB scenario. The numbers represent the order of the movements during one block of the experiment.

approximately 5 m (16.5 ft.) back and to their left. The LB scenario replicated backing on a long straight driveway for approximately 61 m (200 ft) (Figure 5).

The trials took place over 2 days (eight trials per day) occurring no more than 10 days apart. Three unexpected crash scenarios were introduced during Trial 7 of Day 1 and Trials 3 and 7 of Day 2, one involving a decoy surreptitiously placed by a researcher in the driver's blind spot behind the vehicle while in a parking space, and two involving remote sensor activation (no decoy) while the driver was either backing out of a parking space or down a long open portion of the parking lot. The sensor system on the rear bumper of the vehicle was remotely activated by the researcher without the knowledge of the driver (no obstacle was present). The occurrence of three unexpected crash scenarios was counterbalanced across days and participants.

The dependant measures were acceleration, peak velocity ($V_{peak}$), brake reaction time ($t_{RT}$) and braking latency ($t_{BL}$). In this context, *braking latency* is defined as the time from brake onset to maximum brake pedal displacement as measured with a string potentiometer. Acceleration was a measure of velocity change over each 0.1 s time. Brake reaction time was measured from the onset of the warning to the point the brake was applied.

## 4. Results

Below, the estimates of brake reaction time ($t_{RT}$) and braking latency ($t_{BL}$), which were discussed above, are reported. In addition, estimations of peak velocity and backing acceleration are derived.

### *4.1. Brake Reaction Time ($t_{RT}$)*

In 27 of 35 instances, drivers did not respond before impact and struck the surrogate pedestrian with no measurable preimpact response. In eight instances, the driver recognized the pedestrian before backing (as indicated in verbal comments to the experimenter) and did not back. On seven of these occasions, the driver looked into the rearview camera prior to his or her decision. In the 27 instances drivers struck the surrogate pedestrian, and only once did a driver look into the rearview camera view before striking the pedestrian.

Drivers responding to the intentionally activated audible (false) alarm during the SB and LB scenarios responded slower and with larger variance than is typical of forward brake reaction times (all responses $M = 2.6$, $SD = 1.51$ s). Of the 72 false warning response time events (36 SB events; 36 LB events), drivers failed to respond 27 times, and the event did not transpire 14 times. On six occasions drivers were on the brake within 0.2 s of audible warning onset or earlier (they were already on the brake). The other eight instances involved the string not being properly pulled or the warning not occurring due to equipment failure.

Drivers backing a long distance responded slower than those backing a short distance. Using the Wilcoxon signed-rank test for nonparametric distributions, brake reaction times for short and long backers were compared. Average brake reaction time of short backers was 2.09 s ($SD = 1.52$ s), and average brake reaction time for long backers was 2.88 s ($SD = 1.47$ s). The difference was significant based upon negative ranks Z ($n = 31$) = –2.676, $p = .007$. By squaring the standard deviations, we see that an assumption of a Poisson distribution (the variance equals the mean) would very closely model the distribution of brake reaction times.

When evaluating driver response times, we must consider the percentage who fail to respond, or conversely, the percentage who did respond. In this experiment, short backers responded 11 of 34 times (32%), whereas long backers responded 20 of 35 times (57%).

### 4.2. Time to Peak Brake Pedal Displacement: Braking Latency ($t_{BL}$)

Generally, drivers backing longer distances depressed the brakes slower than drivers who were backing a short distance. Although informative, the differences between the long and short backers in the average time to peak braking did not reach statistical significance with a Wilcoxon signed-rank test (Z = –1.305, $p = .192$). Short backers took an average of 1.15 s ($n = 11$, $SD = .98$) to reach peak pedal displacement and long backers took 1.69 s ($n = 25$, $SD = 1.62$).

### 4.3. Initial Peak Velocity ($V_{max}$)

Peak velocity was determined by finding the point on the velocity versus time graph at which the change in the velocity over the change in time reached an asymptote over a 0.2-s sample ($\partial v/\partial t = 0$). For example, if the scalar velocities over a 0.2-s period decreased (or the negative velocity vector increased) or remained constant, then the velocity at that point was reported. The time of 0.2 s was selected to ensure the peak was not due to an anomalous reading or slight hesitation in the acceleration. In a few instances, the velocity decreased followed by a subsequent increase much later in the backing. Therefore, drivers may reach a higher velocity when backing, but they would do so only after a longer period of backing that would exceed the backing distances examined in the current research.

Drivers backing a short distance reached an average peak velocity of 2.68 mph ($SD = 1.25$), whereas those backing a longer distance reached an average peak velocity of 6.17 mph ($SD = 1.77$). During the LB, all drivers reached a peak velocity within 15 m (50 ft). The overall average peak velocity was 4.6 mph. These results are very similar to those of Harpster, Huey, and Lerner (1996) who stated “except for extended backing maneuvers maximum backing velocities averaged around 4.8 km/h (3 mph), and did not exceed 11.3 km/h (7 mph)” (p. 895) (Figure 6).

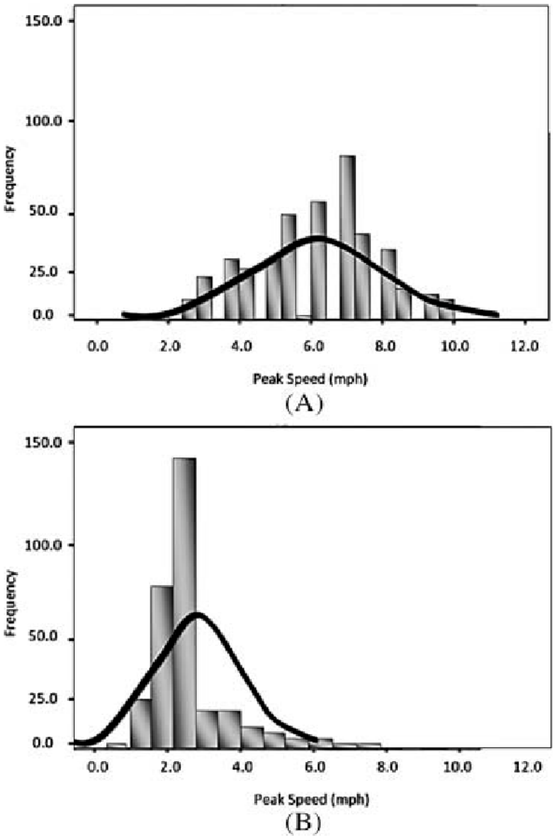

**Figure 6.** Distribution of peak velocities during long backing (left) and short backing (right).

### *4.4. Backing Velocity and Acceleration*

Our goal is to identify a key to discriminate short (slower) from long (faster) backers. Velocity and acceleration are two possible tools to differentiate between these two sets of backers during the first phase of the acceleration. We first address the distribution of the velocities obtained during the two backing maneuvers and then discuss how that relates to acceleration. Our method of data collection allows one to see the variance of times to reach each velocity for the different backing maneuvers.

There were 316 SB scenarios in which data was collected (some data was lost due to equipment failure, experimenter error, and instances where the driver chose not to back due to the obstacle). In 207 SB instances, drivers reached a velocity of 2 mph, and only in 39 instances did drivers reach a velocity of 4 mph. Similarly, there were 393 LB scenarios where data was collected; 389 reached 2 mph, 340 had a peak in excess of 4 mph, 236 reached 6 mph, and 64 had a peak velocity in excess of 8 mph. Those who back a longer distance did so at a significantly greater acceleration, with 704 of 705 long backers having higher accelerations than short backers ($Z = 17.585$, $p = .000$).

The maximum peak velocity for short backers was 2.68 mph. If we set 4.00 mph as the dividing point between short and long backers, we would miss a short backer some 15.8% of the time and would falsely identify a long backer as a short backer some 13.5% of the time. The optimal threshold depends on the costs of hits, misses, false alarms, and correct rejections, so without such knowledge one cannot move forward and determine what ultimately the percentage of misses and false alarms would be with a device that used

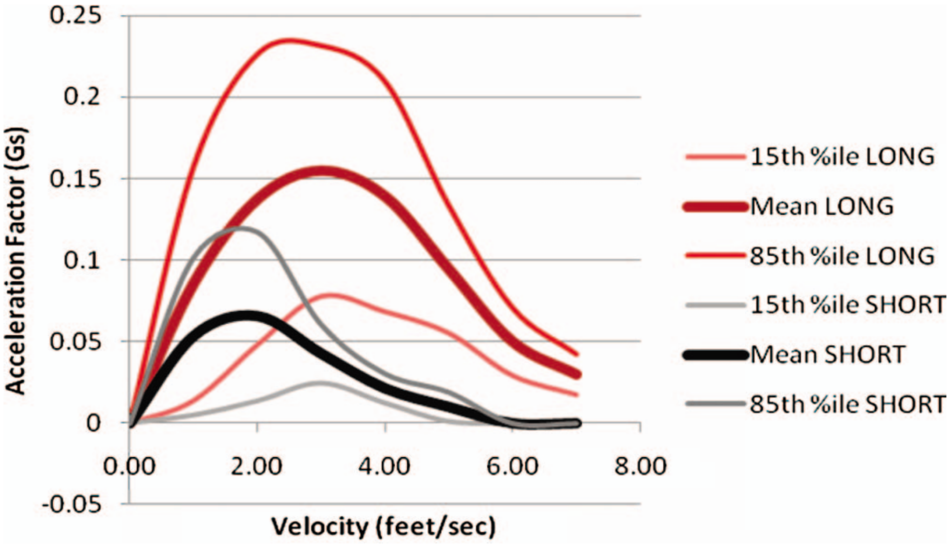

**Figure 7.** Velocity by acceleration factor profiles for short and long backing. (Figure provided in color online.)

just velocity. Still, though velocity may be a good method of discerning short from long backers, vehicle acceleration was much better.

To derive the acceleration, we first needed to determine the time necessary for the drivers to move from a stop to a velocity of 1, 2, 3, . . . , *m* mph. From the time to reach each velocity we are able to derive the acceleration of the drivers at each velocity using Equation 3.

$$\mu = \frac{V_o}{(g \times t_m)} \tag{3}$$

From our results (Figure 7), a driver backing at 0.06 Gs over the previous 0.1 s is most likely intending to back a longer distance and attain a peak velocity near 9 ft/sec. Fewer than 15% of long backers accelerate at less than 0.06 Gs, and only 25% of short backers accelerate greater than 0.06 Gs within the first 1.5 s of backing. Even when identified incorrectly, the acceleration tells the system vital information. For instance, a short backer who is accelerating sharply should be identified as a faster backer. Also, a long backer who is accelerating slowly needs a shorter detection range based upon his or her current state. The results from drivers in this research show that after backing a little more than 2 ft, an acceleration of greater 0.06 Gs could identify a fast backer (a driver who attains a peak velocity greater than 5 mph) from a slow backer (a driver who never reaches a velocity of 5 mph) with better than 95% certainty. Furthermore, if a short backer is accelerating at a rate greater than 0.06 Gs, he or she will likely attain a peak velocity near that of a long backer. Predicting such a driver will attain a velocity near 6.2 mph will not be an error most of the time.

Because we did not gather acceleration at all velocities and because individuals accelerate differently at the same velocity, we would like to be able to predict the acceleration at any given velocity. A regression analysis was used to determine that a cubic function, presented in Equation 4, best modeled acceleration as a function of velocity as seen in

**Table 2**
Coefficients Applied to Equation 2 for Short and Long Backing Acceleration Functions

| Backing Distance | $a_2$ ($m^{-2}$) | $a_2$ ($m^{-1}$) | $a_1$ (−) | $a_0$ (m) | $r^2$ | $F_3$ |
|---|---|---|---|---|---|---|
| Short | 0.002 | –0.022 | 0.066 | 0.003 | 0.933 | 18.55* |
| Short 15th percentile | 0.000 | –0.004 | 0.014 | –0.003 | 0.601 | 2.005 |
| Short 85th percentile | 0.003 | –0.039 | 0.112 | 0.010 | 0.888 | 10.59* |
| Long | 0.002 | –0.032 | 0.128 | –0.003 | 0.990 | 132.21* |
| Long 15th percentile | 0.000 | –0.005 | 0.041 | –0.008 | 0.871 | 8.97* |
| Long 85th percentile | 0.004 | –0.056 | 0.213 | 0.000 | 0.995 | 267.35* |

*signifies significance at greater than $p = 0.05$.

Figure 7. The coefficients, variance and significance are displayed in Table 2.

$$A = f(V) = a_3 \times V^2 + a_2 \times V^2 + a_1 \times V + a_0 \tag{4}$$

## 5. Conclusions and Discussion

Alarmingly, more than one half the drivers failed to respond. The most common participant explanations for failing to respond were not hearing the warning or not appreciating its purpose. Some who did not respond failed to discern the warning; some did not have time to respond. There is a need to examine the effectiveness of warning sounds, yet a more efficient algorithm that accounts for the drivers' response times, backing acceleration profiles, and peak velocities will allow for an earlier warning and fewer nuisance warnings. A system with fewer nuisance warnings will likely demand more respect and attention to the warning.

Short backers responded faster and reached a maximum displacement of the brake pedal earlier than long backers. Brake reaction time and braking latency decreased for short backers, but the probability of responding was much less and the coefficient of variation (*SD/M*) was more than 20% greater than LB responses.

Response times decreasing as the probability of response failure increases is typical of a responder who is overburdened (at the far right of the Yerkes-Dodson, stress vs. performance curve; Yerkes & Dodson, 1908). This result may be due to anchoring effects or a refractory period (a response inertia). During a SB scenario the warning was offered relatively close in time to the moment the driver moves his or her foot from the brake to the accelerator pedal (much closer in time than the LB scenario). To return the foot back to the brake may require additional mental workload involved when switching mind-sets.

The sensor system in the vehicle tested offered an audible warning when within 2 m (6 ft). We must agree with Mazzae and Garrott (2008) who concluded “Based on calculations of the distance required to stop from a particular vehicle velocity, detection ranges exhibited by these systems were not sufficient to prevent many collisions with pedestrians or other objects” (p. 6). We should again point out that the current systems are designed for parking assist, not collision avoidance. However, we would add that some drivers were able to avoid hitting the surrogate pedestrian with the aid of the backing camera system and warning. It is clear that the combination of an audible warning and a camera system will likely reduce a small percentage of crashes, but with system modifications the combination has the potential for much greater improvement. Given the current short sensing range, automatic braking may also be an option, particularly because there is no significant likelihood of anything but a backing collision. Several manufacturers have a system that stops vehicles during low-velocity following, such as Volvo's City Safety system (Volvo New Events, 2009). If applied to rear backing, such a system would circumvent a poor response by a driver and may allow for shorter sensing ranges and assumptions of shorter brake reaction times and braking latency times in the stopping threshold algorithm. Our results corroborate the findings of Lerner, Kotwal, Lyons, and Gardner-Bonneau (1996) who recommended that a back-up warning device should include a cautionary and a danger warning signal based on time to collision, if the danger warning also involves a braking assist of some type. At the very least, the results noted in the current research, and the research of others, suggest the current sensing range is too short for long backers and not informative enough for short backers.

Harpster et al. (1996) showed drivers typically travelled fewer than 2.44 m (8 ft) in the first 2 s, which is an average acceleration of 0.12 Gs. According to Williams (1999) peak average acceleration of 0.07 Gs was the most common. These studies did not report the backing distances. When compared to the results of the current research, the results from Harpster et al. (1996) are consistent with our long backers, and the results by Williams (1999) are consistent with the average acceleration of short and long backers.

### 5.1. *Implications Relative to Collision Avoidance*

There are several considerations that must be addressed before a backing warning system is implemented or proposed (Llaneras et al., 2005). The warning system used in the current research had a rearview camera system, beeping noises from within the vehicle, and light warnings. The primary focus of the current research is to propose a backing warning system that will understand and supplement the abilities of a driver. The current research did not address the location of the warning, nor the type of warning. A sound emanating from the direction of the hazard may offer a driver additional context (Wallace & Fisher, 1998). A location-based warning may also benefit a pedestrian who is able to appreciate the warning and avoid a crash (Lancaster, Alali, & Casali, 2007). Also, Sullivan and Buonarosa (2009) found that natural sounds resulted in the shortest response times. We noticed drivers responded quickly to the tap noise caused by striking the surrogate pedestrian, but rather slow to the beeping noise. If the warning could mimic an impact in sound and location, it is likely that performance would improve.

On the basis of the literature and this research, there are two primary concerns. First, the system must assist a driver who is parked from backing in unsafe conditions. Second, once backing, the system should offer an effective warning in a timely manner without an intolerable number of nuisance warnings.

SB conditions replicated a situation in which a driver was starting from a parked position. When responding to a surrogate pedestrian placed directly behind the SB vehicle, 27 of 35 failed to respond. Short backers responding to a false warning failed to respond 23 of 34 times, and long backers failed to respond 15 of 35 times. Overall, short backers failed to respond 72% of the time. Whether this is due to anchoring, refractory periods, workload, or any other reason, these drivers were incapable of responding appropriately to a hazard shortly after the commencement of braking. The only drivers who did not strike the surrogate pedestrian were those who recognized the hazard when stopped. Seven of eight drivers who did not back into the surrogate pedestrian first looked into the rear camera view. When stopped, a brake lock mechanism that requires a driver to override the system, or a vehicle actuated stuttering (pulsating braking application) may improve driver performance (analogous to a rumble strips for backers).

Once backing, short and long backers exhibited different behaviors. Drivers reached an average peak backing velocity of 2.68 mph for SB and 6.17 for LB. Long backers (those who are backing at greater velocities) will need a greater warning distance to be able to respond and stop before striking the object the sensor detects.

A warning distance (WD) or the range at which a warning is initiated is critical. Too large a range contributes to nuisance warnings and too small a range contributes to determine inadequate time for crash avoidance. As mentioned earlier, additional research is necessary to determine the optimal acceleration and detection range thresholds after a cost–benefit analysis. Approximately one half of those who participated in this research reported previously driving an SUV for personal use. Although attempts were made to allow the users to become comfortable with the vehicle, drivers who customarily drive high-profile vehicles may differ from those who do not.

### *5.2. Adaptive Warning Algorithm*

The goal of our proposed system is to be adaptive to the vehicle velocity, acceleration, stopping ability, and drivers' abilities and then adjust the warning distance accordingly. Consideration should also be given to the blind spot of the particular vehicle as well as parking space size.

*Warning distance (WD).* The length of the warning distance should be based upon the total stopping distance (TDs) that is equal to the response distance ($\mathrm{D_{RT}}$) plus the stopping distance ($\mathrm{D_S}$) (see Table 1 for definitions.) The WD must be greater than the TDs because it does not suffice to stop at impact (on a small child). A warning should be given immediately if the range at which the obstacle is detected is shorter than the TDs. Equation 5 shows the relationship between the required warning distance and the range and the total stopping distance.

$$\mathrm{WD} > \mathrm{Min(R, TDs)} \tag{5}$$

*Response distance ($D_{RT}$).* Response distance is based upon the velocity when the object first comes within range of the sensor ($V_O$) and the sum of all time components involved in the response. For a warning system, three time components must be addressed by the system, hazard detection/warning system latency ($\mathrm{t_{SL}}$), braking reaction time of the driver ($\mathrm{t_{RT}}$), and braking (vehicle) latency ($\mathrm{t_{BL}}$) (see Table 1 for definitions). Vehicle acceleration will influence the distance traveled during the response as described in Equation 6 (the terms in this equation are defined in Table 1).

$$\mathrm{D_{RT}} = \left(\mathrm{V_0} \times \sum_{\mathrm{i}\in \mathrm{S}} \mathrm{t_i}\right) \pm \left(\frac{1}{2} \times \mathrm{g} \times \mu \times \sum_{\mathrm{i}\in \mathrm{S}} \mathrm{t_i^2}\right) \tag{6}$$

$$\mathrm{S} = \{\mathrm{SL, RT, BL}\}$$

*Stopping distance ($D_s$).* The stopping distance is a prediction of the distance the driver will need to stop in the applicable scenario (SB or LB). That calculation requires knowing how fast the vehicle is traveling after the warning time, brake response time, and brake latency have elapsed. Refer to this velocity as $\mathrm{V_f}$. The range and peak velocity will depend on the scenario (SB or LB). If the driver is accelerating when backing, the system predicts the peak velocity that the vehicle will attain (given the current velocity and the range at detection). If there is sufficient distance to accelerate to a velocity greater than average peak velocity, the final velocity is assumed to be the average peak velocity (see Equation 7).

$$V_f^2(SB) = MIN\left(V_{peak(SB)}^2,\ V_o^2 \pm 2 \times g \times \mu \times MIN\left(R_{SB}, D_{RT}\right)\right) \tag{7a}$$

$$V_f^2(LB) = MIN\left(V_{peak(LB)}^2,\ V_o^2 \pm 2 \times g \times \mu \times MIN\left(R_{LB}, D_{RT}\right)\right) \tag{7b}$$

Equation 2 describes the stopping distance calculation. (American Association of State Highway and Transportation Officials [AASHTO], 2004) utilizes a deceleration rate ($\mu_d$) of 0.4 Gs for velocities of 20 mph (and presumably less). Llaneras et al. (2005) reported an average deceleration of 0.27 Gs. Warner, Smith, James, and Germane (1983) reported deceleration of greater than 0.6 for travelled asphalt. For design purposes, we see no reason to differ from the design guidelines suggested by AASHTO.

*Short and long backing scenarios.* Short backers travel slower velocities, which will allow them to be able to respond effectively if given shorter warning distances. Longer backers, who travel at greater velocities, need an earlier warning. The range at which the backing sensor monitors obstacles behind the vehicle should be adaptive to short ($R_{SB}$) and long backers ($R_{LB}$). Based upon the findings of this research, the system should monitor the acceleration and velocity. If a driver is traveling 1 mph with an acceleration of greater than 0.06 Gs, the driver is likely a long backer and will likely increase his or her velocity to an average 6.2 mph. However, if the vehicle is traveling 2 mph with an acceleration of 0.05 Gs, that driver will likely be approaching his or her peak velocity of near 2.7 mph (Figure 7).

This information is perhaps the most significant finding of this research in that it allows the system to project the future behavior of the vehicle (Figure 8). Briefly, when the sensor is triggered, the velocity is sampled. If the velocity is less than 1 ft/s and the deceleration is greater than 0.06 Gs, then the driver is assumed to be in a LB scenario.

The sensor system will evaluate the situation based upon the projected velocity of the vehicle rather than the current velocity. The assumed peak velocity will be the minimum of the average peak velocity or the peak velocity that the vehicle will attain given the constraint of the current range, velocity and acceleration. Equations 7 and 8 depict how the final velocity is determined:

The anticipated velocity of the vehicle was based upon the integral of the acceleration profile from the current velocity to the minimum of the current velocity or peak velocity as shown in Equation 8.

$$\int_{V_o}^{V_f} \frac{f(V)}{\Delta V} \tag{8}$$

After projecting the final velocity, the system will calculate the distance necessary to stop if traveling the projected final velocity. If the vehicle is decelerating when detection occurs a minus (–) would replace the (+/–) in Equation 7. If decelerating, the projected final velocity would be less than the current velocity and the situation would be less severe than if the vehicle were accelerating. The stopping distance is dependent upon the velocity of the vehicle and the deceleration of the vehicle. The objective of this algorithm is to forecast the velocity that a backing vehicle may attain. For example, if backing at a fast rate, but given a short range, the peak velocity will be constrained.

The assumed peak velocity is based upon the current velocity and acceleration. If the velocity is less than 1 mph, and the acceleration is less than 0.07, the vehicle will likely

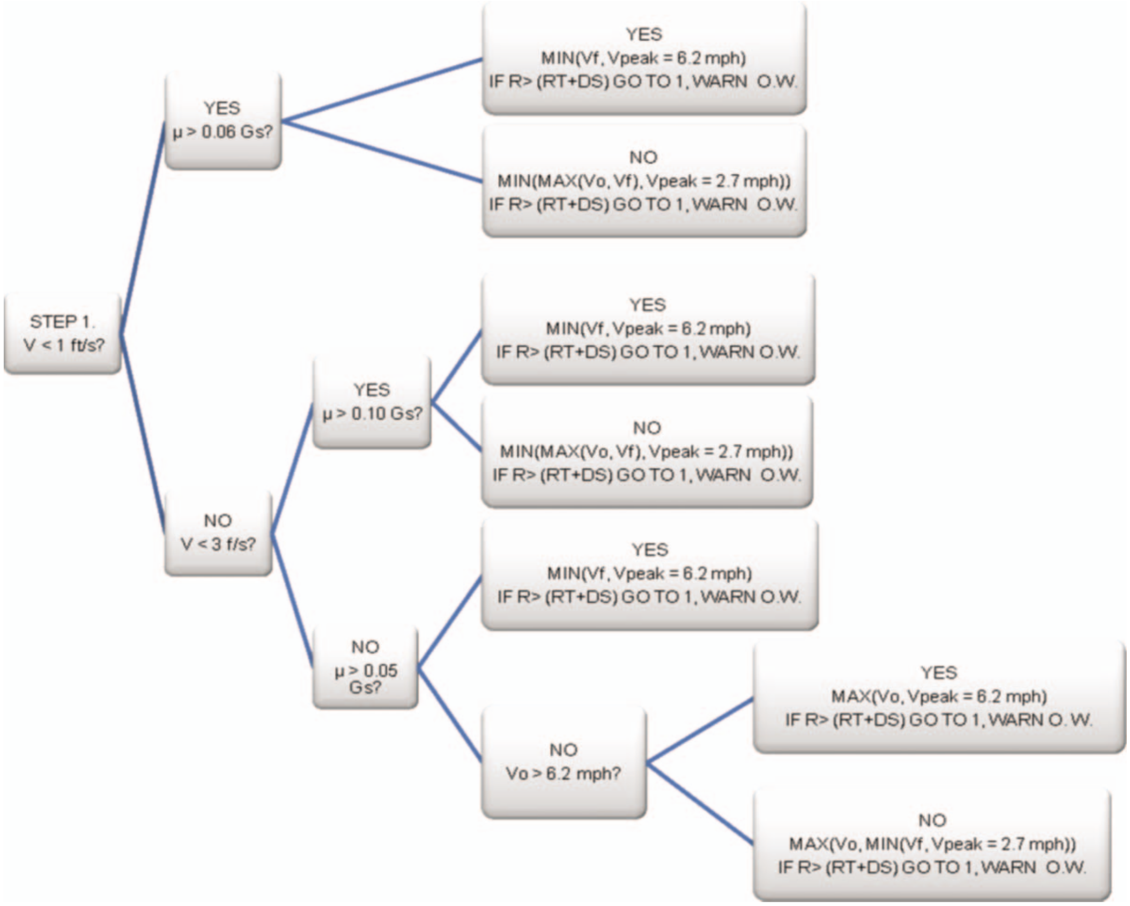

**Figure 8.** Flow chart showing the decisions leading up to a warning. *Note:* The final velocity will be the minimum of the peak velocity, or the maximum of the initial velocity versus final velocity. The system will then base a warning decision on the stopping kinematics of the predicted final velocity. If no warning is triggered, the system recycles from Step 1. O.W. = otherwise. (Figure provided in color online.)

reach a velocity near 6.2 mph. Yet if the vehicle is traveling 2.5 mph with an acceleration of 0.02 Gs, the driver is likely reaching his peak velocity. Equation 8 defines the portion of the cubic functions from Equation 4 and Table 2 that will be utilized and when. Again, the system will assume that the driver will reach peak velocity for the particular backing maneuver and will accelerate in the manner as depicted in Figure 7.

$$f(V^{\pm}) = \begin{cases} \dfrac{V_{peak} - V_o}{t_R} A^{+/-} \\ \dfrac{V_o}{t_R} A_{constant} \end{cases} \tag{9}$$

The polynomial f(V) is an acceleration function that considers the difference between the peak velocity and $V_o$ depending on whether the vehicle is accelerating. The polynomial is a function that we fit to the backing data to determine the time that it takes the driver to reach the peak velocity (Equation 4; Table 2).

After measuring several vehicles types, one study indicated that a 0.6 m object could not be seen any closer than 4.5 m to 9 m (15 to 30 ft) from the rear of most station wagons and SUVs (Paine & Henderson, 2001). Consumer Reports (2005) measured the blind spots of several vehicle types and reported the average blind spot for a sedan to be 3 to 10.7 m (10 to 35 ft) while SUVs and pickups had an average blind spot of up to 15.2 m (50 ft). The typical parking space in the United States is 5 to 6 m (16 to 20 ft) deep. Because most drivers of high-profile vehicles cannot see the area up to 6 m (20 ft) to the rear of their vehicle, it would be logical to have a detection system monitor that area.

If we apply what we learned from the current research to the average long backer, the average driver needed 3.5 s to perceive, respond, and fully press the brake when responding to the beep warning. If the sensing system latency samples at 4 Hz, the total time component would be near 3.75 s. Given a 0.4 G deceleration, a long backer would need a warning in excess of 6.7 m (22 ft). Either the sensor range must be increased or the warning type improved, or more likely both.

The findings proposed here are somewhat corroborated by the consistent findings of Llaneras et al. (2005) who found that drivers given a longer warning distance responded more efficiently and reported the warning as being more timely.

Additional system constraints may reduce nuisance alarms. The comparison of effective warnings to nuisance warnings will likely improve with a system that models acceleration and velocity, rather than range only (as is the case with the current parking assist systems). For example, if at 6 ft and traveling 2 ft/s but decelerating, the warning would not yet be given. In that same example, a warning would be given with the vehicle we tested. Another consideration could be the rate at which the obstacle is crossing behind the vehicle (it may clear before arrival). Additional research into the influence of camera glances is recommended as well.

A method has been proposed based upon total stopping distance and blind spot measurements as a warning. Clearly more research is necessary. Future research should examine the influence of a better warning sound, warning direction, self-braking systems, light detection and ranging (LIDAR) versus sonar sensing, and determining the optimal detection ranges that would account for the most dangerous situations yet keep nuisance warning to a minimum.

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