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Application of a Crash Prevention Boundary Metric to a Road Departure Warning System

S. Szabo
National Institute of Standards and Technology
Gaithersburg, MD 20899
B. Wilson
Volpe National Transportation Systems Center
Cambridge, MA 02142

ABSTRACT[1]

The U.S. Department of Transportation is actively involved in assessing the benefit of road departure warning systems (RDWS). A crash prevention boundary (CPB) metric has been proposed as one means of objectively measuring system performance. This paper presents the results of applying the CPB metric to data collected during the validation of an experimental RDWS. Two types of road departure warning scenarios are examined: curve speed and lateral departure.

KEYWORDS: *road departure, crash warning system, metrics, crash prevention boundary*

1 INTRODUCTION

The U.S. Department of Transportation is actively involved in assessing the benefit of road departure warning systems (RDWS) that may help reduce the number of collisions and deaths. Many types of metrics designed to objectively quantify warning system performance are being considered. The crash prevention boundary (CPB) metric can be used to determine the amount of acceleration required to avoid a crash as a function of the timing or location of a warning [1][2]. A series of tests consisting of potential crash scenarios designed to elicit a warning [3] were conducted using an experimental RDWS. Data was collected during the test using an independent measurement system. The data was analyzed using the CPB metric, with a focus on evaluating the timeliness of the warning. The warning system provided a warning in almost all cases, but a determination of whether the warning was late or early relied upon a pass/fail criterion established by the warning system's designers. The government is interested in establishing a baseline of acceptable system performance, which is intended to help convince the driving public that these systems provide a worthwhile benefit. The CPB metric may prove useful in establishing a performance baseline. This paper shows how the CPB metric can be used to analyze two types of road departure warning scenarios: curve speed and lateral departure. For this particular warning system, the results of the CPB analyses indicate that the deceleration required to negotiate a curve safely has a markedly different profile than the lateral acceleration required to avoid running off the road.

A measurement system for analyzing warning system performance is also described. The paper closes with some recommendations for future warning-algorithm metrics and design guidelines.

2 MEASUREMENT SYSTEM

An independent measurement system (IMS) was developed by National Institute of Standards and Technology (NIST) for evaluating warning system performance. The IMS allows evaluators to measure performance without relying on the system under test for sensor data. In addition, the IMS provides redundancy, quality control and an opportunity to collect miscellaneous data for additional analysis (e.g., data for validating the CPB metric was collected using the IMS). The IMS consists of three video cameras mounted on a detachable roof rack (Figure 1) and a fourth camera pointed at the warning system's dash display. A microphone is located in the cab to capture the audible warnings issued

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by the system and to capture comments from the driver. The videos from the four cameras are fed into a multiplexer producing the image shown in Figure 2. The output of the multiplexer is recorded onto a digital video recorder (DVR). A GPS antenna is mounted on the roof and the raw output of the GPS receiver is recorded on the second audio channel of the DVR at a one Hz rate, ensuring that the GPS data is synchronized with the output from all four cameras. The GPS data is post-processed using National Geodetic Survey Continuously Operating Reference Stations (http://www.ngs.noaa.gov/CORS). The side and forward cameras are calibrated so that pixel coordinates can be transformed into ground coordinates either in a GPS-referenced coordinate system or in a local-vehicle coordinate system. Analysis software is used to view video and the vehicle's trajectory, for making measurements to lane markers and obstacles, and for calculating a curve's location and radius.

Figure 1. Three weatherproof cameras mounted on roof rack.

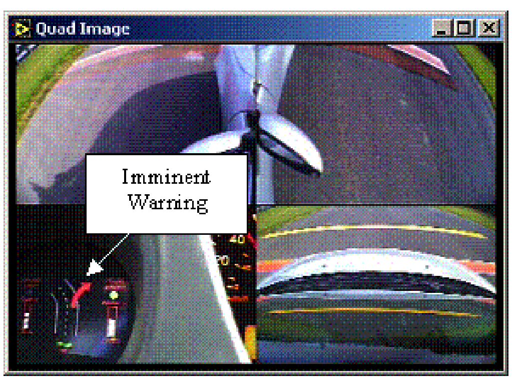

Figure 2. Images from roof-mounted cameras and dash-view camera are multiplexed into a single quad image. The dash-view camera shows an active imminent warning icon.

3 CURVE SPEED CRASH PREVENTION BOUNDARY

Curve speed tests consist of a vehicle traveling straight toward a curve at an excessive speed. Figure 3 shows the geometry used for the CPB analysis. The curve shows a critical point (CP) a short distance into the curve. The warning is given at a distance of x (meters) prior to the CP.

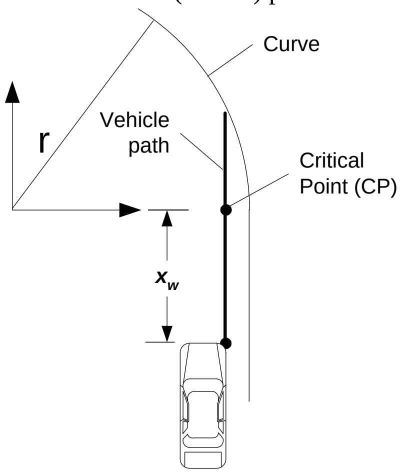

Figure 3 Geometry of curve speed test

Drivers who receive a legitimate warning (a true positive) have a range of reaction times and decelerations levels available to them sufficient to avoid a collision. The locus of the required deceleration versus the reaction time is known as the CPB. The following equation provides the CPB for the curve speed-warning situation depicted in Figure 3. This version of the CPB equation relates warning location to the required longitudinal deceleration for negotiating the approaching curve using the following equation:

$$d_{req} = \frac{v_o^2 - v_s^2}{2(x_w - t_r v_o)} \qquad \textbf{(1)}$$

Where:

v_0 = vehicle initial forward speed
v_s = safe speed for the curve
t_r = driver reaction time
x_w = the distance between the warning location and the CP
d_{req} = the deceleration required to reach the safe speed at the CP

Although details of the RDWS warning algorithm are proprietary, a public algorithm under development by the Applied Physics Laboratory and NHTSA [4] provides insight into the general warning process. The algorithm assumes a warning system has different sensitivity settings that will affect the location of a warning. The settings use values for the desired limit of lateral acceleration (A_s) in a curve and longitudinal deceleration before the curve (D_W). The lateral acceleration limit is used to determine the safe speed going into the curve as follows:

$$v_s = \sqrt{A_s r} \qquad \textbf{(2)}$$

The values for each setting used in this analysis are given in Table 1. A near setting means that the driver would like a warning closer to the curve's entry, which means that the driver is comfortable applying a greater deceleration before the curve and carrying a higher lateral acceleration through the curve. One can think of these values as defining a typical driver's projected velocity profile for the curve-warning algorithm. The first phase of the profile has a constant velocity equal to v_0. The warning occurs and the velocity is maintained for 1.5 s. Afterwards, the velocity ramps down based on D_w until v_s is reached.

Sensitivity Setting		A_s	D_w
1	Near	0.42 g	0.70 g
2	Near-mid	0.36 g	0.60 g
3	Mid	0.30 g	0.50 g
4	Mid-far	0.24 g	0.40 g
5	Far	0.18 g	0.30 g

Table 1 Sensitivity settings for APL/NHTSA CSW public algorithm.

The curve speed test was conducted on the Transportation Research Center (TRC) winding road course (Figure 4) on October 2, 2003. The vehicle starts at point E, reaches a speed of 50 mph (22 m/s) by point D and travels through curve C. The vehicle should provide a warning before reaching curve C. The radius of curve C, measured using the IMS, is 115.7 m ± 0.5 m. The vehicle speed during each test, measured using the GPS, was 48.8 mph ± 0.05 mph (21.8 m/s ± 0.02 m/s). The lateral acceleration (v^2/r) in the curve if the speed is maintained is 0.42 g.

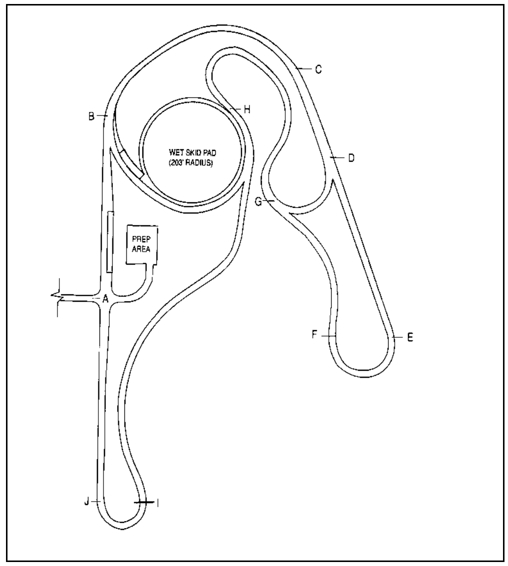

Figure 4. TRC winding road course. Analysis was performed on data collected from test runs where vehicle travels from E into curve C.

The experimental warning system produces two levels of warning: cautionary and imminent. As a driver approaches the curve at an excessive speed, the system will first issue a cautionary warning. If the driver fails to reduce the vehicle's speed, the system will then issue an imminent warning. Figure 5 shows test results for cautionary warnings and Figure 6 shows test results for imminent warnings. Each crash prevention boundary curve in the figures is plotted using equation (1), with the mid-level sensitivity setting used to determine the safe speed and x_w set to the location of the warning for a given run. Based on the location of the warning, the curves describe the required longitudinal deceleration to reach the safe speed for a given driver reaction time.

The plots should *not* be interpreted as classical CPBs. In a classical CPB, a driver reacting to a warning must decelerate at a level *above* the level shown in the curve that corresponds to the specific lapse between the warning and the driver's response. For example, CPBs for slower and stopped lead vehicles [5] specify the required decelerations for cases in which a following vehicle is approaching a lead vehicle and receives a rear-end collision warning. Drivers decelerating at lower levels than those provided by the curves will crash. In the longitudinal CPBs in Figure 5 and Figure 6, in contrast, drivers that take longer to react and decelerate less will not necessarily crash. Rather, they will need to negotiate the curve, at least initially, faster than the safe speed in equation (2). Section 5 will comment on this.

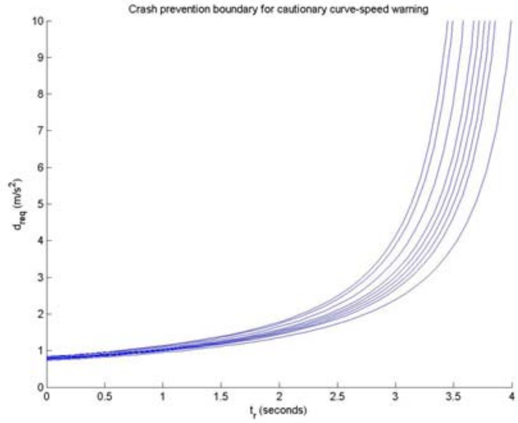

Figure 5. Longitudinal CPB for series of cautionary warnings. Each curve corresponds to the location of a warning during test runs.

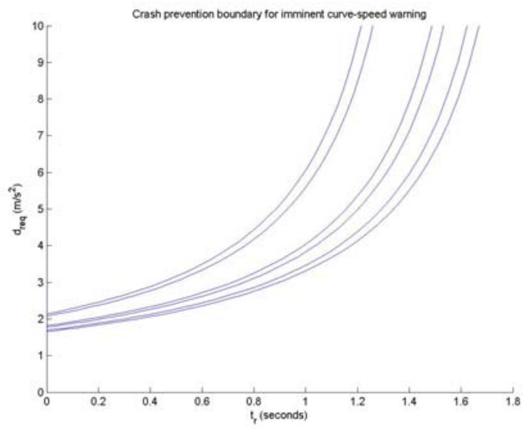

Figure 6. Longitudinal CPB for series of imminent warnings

4 ROAD DEPARTURE CRASH PREVENTION BOUNDARY

Lateral drift tests consist of a vehicle traveling at a constant speed and departing the road at a constant angle. Figure 7 shows the geometry for a lateral drift into a jersey barrier. The location of a warning, y_w, is the distance from the vehicle to the road edge (or other boundary) at the time of warning. A warning should provide the driver time to react and steer away from the road boundary.

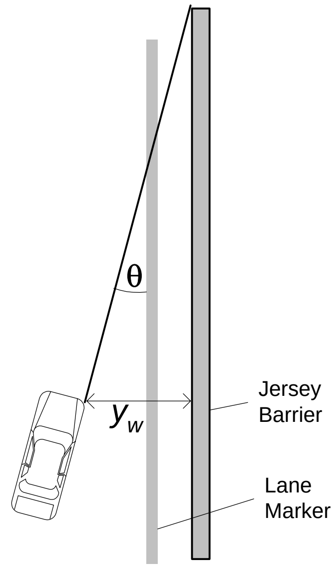

Figure 7. Geometry of a lateral drift test. In this test, the Jersey barrier is the road boundary.

Reference [2] also provides a CPB equation that can be used to relate warning location to the required lateral acceleration to avoid a lateral departure using the following equation:

$$a_{lat} = \frac{(v\theta)^2}{2(y_w - t_r v\theta)} \qquad \textbf{(3)}$$

Where:

v = vehicle forward speed
θ = departure angle
a_{lat} = lateral acceleration used to avoid departure
t_r = driver reaction time
y_w = the distance between the warning location and the road boundary

The validation tests for the warning system examined for this paper specify a lateral velocity during a departure as opposed to a departure angle. The following equation is used to relate lateral velocities measured during a test to departure angle required in equation (3) (this relationship is based on the tangent of the θ, which for small angles is equivalent to θ):

$$\theta = \frac{v_{lat}}{v_{long}} \qquad \textbf{(4)}$$

Where:

v_{lat} = lateral velocity
v_{long} = longitudinal velocity (i.e., forward speed or just v)

Figure 8. Test set-up for road departure toward jersey barrier.

One type of test used to analyze the warning system is the continuous obstacle test, which consists of a straight lateral departure onto a shoulder with a jersey barrier offset 1 meter from the inside edge of the lane boundary. Tests were conducted at the TRC skid pad using a water-filled jersey barrier (Figure 8.). Cruise control was used to set the forward speed during the test at 40 mph (18 m/s). The specified lateral velocity for the test (i.e., the velocity toward the barrier) is 0.4 m/s ± 0.1 m/s. The velocities measured using the IMS ranged from 0.3 m/s to 0.53 m/s.

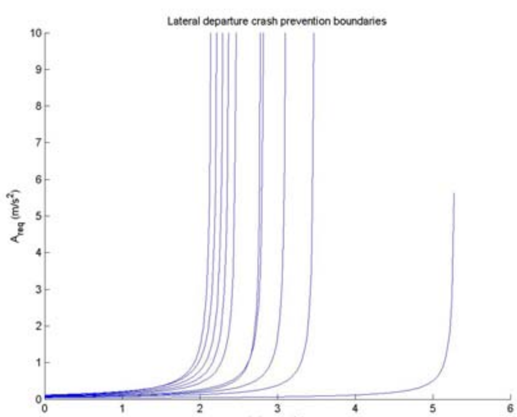

Figure 9. Lateral CPB for series of imminent warnings

Figure 9 shows the test results plotted using the CPB metric. Note that in this case the curves are legitimate CPBs: a driver who receives a warning, steers at some t_r second(s) later, and does not steer with a lateral acceleration greater than that corresponding to the value at this t_r in the appropriate plot will crash.

5 Future Metrics and Design Guidelines

Having developed longitudinal and lateral CPBs in sections 3 and 4, we will now comment on them and their utility as a metric. As indicated, the longitudinal CPB in section 3 is not a true *crash* prevention boundary, because a driver who brakes above the boundary will not necessarily crash. Rather, the driver will be forced to negotiate a curve's critical point at a speed greater than a predetermined safe speed. A driver's skill level and the available traction will determine if a collision occurs.

Despite this limitation, the longitudinal CPB remains a useful metric for both RDWS developers and analysts. A developer can readily understand the implications of a more aggressive warning algorithm, e.g., shown in Figure 6 versus Figure 5. We see in Figure 5, whose CPBs originate from a mid-level (cautionary) warning setting, that approximately 0.1 g of deceleration is required to negotiate the curve safely when the warning is issued. If a driver requires 1.5 second to respond, a deceleration of approximately 0.15 g is required.

In Figure 6, we see that a more aggressive warning algorithm assumes drivers will react more quickly and decelerate at higher levels. Indeed, the change in the CPBs between the cautionary and imminent CPBs in Figure 5 and Figure 6 indicates that in the latter case drivers must react in approximately half the time and decelerate at approximately twice the level as in the former case.

The lateral CPBs shown in Figure 9 all show quite low initial values for the *lateral* acceleration that is required to avoid a road-departure collision (colliding with the barrier). Even 1.5 second later, the required acceleration is still quite low. At reaction times greater than 2 seconds, however, the required acceleration increases markedly.

The different kinematics between curve speed warnings and lateral departure warnings merit comment. We see in equation (1) that the square of vehicle forward speed minus the square of the safe speed composes the numerator of the term that determines the required deceleration. In SI units, 50 mph equals 22.5 m/s and its square is 506. A safe speed of 35 mph results in a numerator of 258, a significant number. The lateral CPB counterpart, equation (3), has the lateral speed as its sole term in the numerator. A lateral speed, even in a departure situation, of 1 m/s is rare, so the numerator of equation (3) typically equals unity or less. Only when the actual reaction time starts approaching the reaction time programmed into the warning algorithm will the denominator of (3) approach 0 and the required lateral acceleration increase rapidly. Thus for curve-speed CPBs, Figure 5 and Figure 6, we see higher initial values and a continuous increase in the required deceleration with reaction time. The lateral departure CPB in Figure 9 shows a lower initial value in the required lateral acceleration and a very flat curve until the reaction time times the lateral speed approaches the alert distance (i.e., until the vehicle is near the road edge or barrier).

Although not technically part of the CPB, we can also use the CPB equations to determine the sensitivity of the required deceleration or lateral acceleration to sensing errors or uncertainty. By taking the derivative with respect to the warning distance, x_w, in equation (1), we can determine the sensitivity of the required acceleration to uncertainty in the warning distance:

$$\frac{d_{req}}{dx} = -\frac{d_{req\_nom}}{x - t_r v_o} \qquad \textbf{(5)}$$

where d_{req_nom} is the nominal required deceleration from equation (1). An initial warning distance of, say, x = 50 m decreases the sensitivity of the required deceleration to errors in the warning distance by a factor of 50. The effect of these errors, however, becomes more pronounced as the reaction distance (initial speed times the time required to decelerate) approaches the warning distance.

The sensitivity of the required lateral acceleration to errors in the lateral distance has a form identical to equation (5):

$$\frac{a_{req}}{dy} = -\frac{a_{req\_nom}}{y - t_r v\theta} \qquad \textbf{(6)}$$

In this case both the lateral warning-position errors and the warning position *(y)* will be smaller than their longitudinal counterparts, so the sensitivity of the required lateral acceleration to lateral sensing errors (or uncertainty) is low, at least when the warning is issued. As the denominator in equation (6) decreases, the sensitivity, of course, increases.

5.1 *Lateral Sensing*

The lateral CPB curves in Figure 9 are highly dependent on the estimated lateral speed and the estimated distance from the road edge (or barrier). The vertical asymptotes occur when the product of the reaction time and lateral speed equals the warning distance. Although there are a number of sensing issues, we will call attention to only one of them: the lateral distance used to issue a warning. The CPBs in Figure 9 result from using the *actual* distance between the vehicle's front bumper and the barrier in the CPB equation (3). The variation in the CPBs results from variations in the initial conditions as well as variations in the lateral-distance estimates. We believe, however, that a reasonable range of initial conditions should not produce variations in CPBs. Drivers should be warned consistently, with the understanding: "You need to steer out of this with a timing and level consistent with how you adjusted the sensitivity." A wide variation in the required timing and level, which will result from improper sensing or processing, violates this understanding and may lead to driver dissatisfaction. The CPB is a useful tool for showing this variation, or lack thereof, for a series of warnings and conditions.

5.2 *Extensions*

As indicated in Section 3, the longitudinal CPB in this paper is not a true CPB because it merely represents the required deceleration to negotiate a curve at a predetermined safe speed. Beyond this issue, however, lies the larger problem of describing a general CPB for negotiating a curve safely. In our tests, we observed that after receiving the alert the driver decelerated and continued decelerating while turning. Other efforts (and expected behavior) demonstrate this same trend: drivers brake before the curve and continue to brake while negotiating curves, at least at the curve entrance. In addition, drivers often "cut" the curve, further complicating efforts to model vehicle motion and crash boundaries. Given that (1) the longitudinal CPB in Section 3 is not a true crash prevention boundary, (2) drivers may exceed the safe speed when entering a curve without necessarily losing control, and (3) drivers cut curves, we see some limitations in applying the existing analyses to describing the CPB of a given curve speed warning. The limitation suggests the need for a more comprehensive CPB, an effort we are pursuing.

6 References

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