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16. Abstract

A leading cause of military vehicle rollover crashes is that one or more wheels move into an area where the terrain falls away steeply or disappears, leading to vehicle rollover. Vehicle-mounted sensors will soon be capable of sensing such hazards in real time. This report addresses the design of a driver interface to provide information about such hazards in a timely and cogent manner in order to allow attentive, distracted, or drowsy drivers enough time and information to avoid the hazard. An interface that consists of an auditory warning and an optional supplementary overlay of the hazard on a driver's-eye view of the roadway is recommended. A set of equations are developed that indicate when the driver must begin applying either a pre-determined level of braking or a pre-determined level of added lateral acceleration to avoid a perceived hazard.

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Providing Drivers With Road-Edge Information to Reduce Road Departure Crashes in a Military Vehicle Fleet

Presented by
University of Michigan Transportation Research Institute

To
Physical Sciences Inc
For task 2 of the project entitled
"Rapid Road Edge Detection Based on Biomimetic Image Processing"

a Phase II SBIR project by Physical Sciences Inc. for the U.S. Army
(SBIR topic A05-222)

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February 26, 2008

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Executive Summary

A leading cause of military vehicle rollover crashes is that one or more wheels move into an area where the terrain falls away steeply or disappears, leading to vehicle rollover. Vehicle-mounted sensors will soon be capable of sensing such hazards in real time. This report addresses the design of a driver interface to provide information about such hazards in a timely and cogent manner in order to allow attentive, distracted, or drowsy drivers enough time and information to avoid the hazard. An interface that consists of an auditory warning and an optional supplementary overlay of the hazard on a driver's-eye view of the roadway is recommended. A set of equations are developed that indicate when the driver must begin applying either a pre-determined level of braking or a pre-determined level of added lateral acceleration to avoid a perceived hazard.

1 Introduction

This document reports on the activities, final products, and recommendations of Task 2 of the project "Rapid Road-Edge Detection using Biomimetic Image Processing." The project is a U.S. Army small business/innovative research (SBIR) project led by Physical Sciences Incorporated. The University of Michigan Transportation Research Institute (UMTRI) serves as a subcontractor for human factors related issues. The project seeks to provide drivers of military vehicles with real-time information about upcoming negative terrain features that may pose a potential threat of vehicle rollover. This is done using forward-looking remote sensors on the vehicle, along with novel sensor processing and fusion methods.

Task 2 is entitled "Analyze Human Factors – I" and has the following goals:

- Develop candidate driver interfaces for the road edge detection system, and
- Develop equations that can serve as the basis of vehicle path prediction and threat assessment algorithms.

Together, these goals address what information to present to the driver, as well as when and how to present that information. Later, in Task 7 ("Analyze Human Factors – II"), a system prototype will be used to present the integrated system to experienced military drivers in order to validate the system concept.

This document addresses only Task 2. The work activities of Task 2 are listed below:

- Problem definition: a definition of scenarios in which the safety system should perform; identification of assumptions; and articulation of system tradeoffs associated with human factors.
- Human-machine interface concepts: a definition of the role of system information that is provided to the driver; identification of candidate approaches to interface design; and a recommended approach.
- Threat assessment: developing analytical equations that can serve as the basis for algorithms that define when to provide the driver with the information..

A simplified view of the sequence of work on these tasks is shown in Figure 1. Scenario definitions and consideration of the scenario dynamics leads to concepts for how system information could assist the driver. Given the information that is to be provided to the driver, threat assessment algorithms are developed based on assumptions of driver responses, sensing capabilities, and other factors. The driver-vehicle interface addresses the details of how the information is presented, e.g., size and design of visual information, and audio tones and volumes. A final step is to consider the outcome of the preceding work tasks and information and insight contributed by the sponsors, and then propose final recommendations for the human factors elements.

The remaining sections address each of the tasks in the bulleted list above.

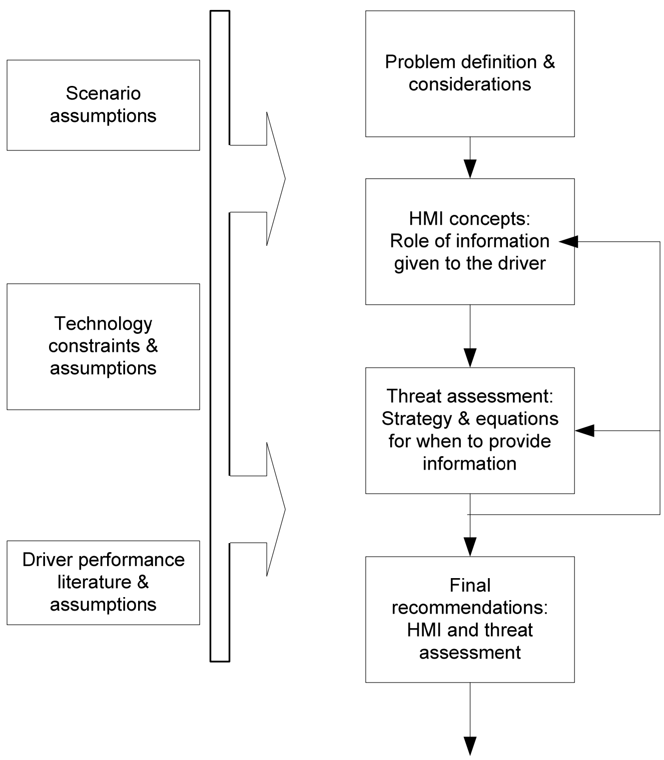


Figure 1. Simplified work activity flow for Task 2

2 Problem definition and considerations

There are countless scenarios involving military vehicles in which negative terrain can contribute to vehicle rollover. Early in the project, two scenarios that were identified by a combined effort of all organizations included:

- Scenario 1: A HMMWV departs from a dirt road into steeper negative terrain during low-speed night patrol (night vision goggles, no headlamps). The primary cause is the driver’s loss of road-edge information due to vehicle geometry (difficulty seeing short-range road features over the hood) and poor demarcation of road edge due to the road being in rough terrain and/or having little motor vehicle traffic.

- Scenario 2: a tractor-trailer combination departs a paved road while traveling at moderate speeds. The primary cause is driver drowsiness or distraction. The road edge would have been readily apparent to an attentive driver.

These scenarios are very different in terms of the information that is needed by the crewman (continuous information vs. momentary warning), the likely state of the driver (fully attentive vs. distracted or possibly drowsy), the possible role of visibility issues, and the evasive action that would be more effective (braking vs. steering). Because these and other dimensions of scenarios may have substantial influence on decisions for the human factors elements, an effort was made to develop assumptions regarding the basic casual factors behind negative terrain-induced rollovers, as well as the identification of selected tradeoffs that may impact the design of a driver interface. Detailed military crash statistics to support these assumptions were not available. The next three subsections present some assumptions regarding the scenarios to be targeted by the system (at least from the driver interface perspective); the causality of the crashes; and the response of drivers to information that may be presented about the negative terrain rollover risk. Together, these set the context for considering an effective driver interface design, which is presented in Section 3.

2.1 Assumptions

This section presents high-level assumptions but is not intended to be a comprehensive list of assumptions.

Hazards

The intention of the system is assumed to be providing the driver with assistance in avoiding driving into a negative-terrain hazard that is located on, or near, the roadway. Figure 2 shows four types of hazards, four of which are assumed to be relevant to the intended system. Three of these hazards are located at, alongside, or near the roadside. These may include drainage ditches, waterways that pass under the roadway, craters, culverts, terrain dropoffs, and others. Furthermore, consideration is given to hazards that intrude into the roadway (but do not block the roadway). These intruding hazards may be avoided by steering, and include situations such as craters or partial washouts. Although Figure 2 shows rectangular hazards, this is for simplicity and does not represent an assumption about hazard geometry.

Figure 3 is intended to illustrate that this work includes situations in which the hazard is indeed quite close to the vehicle but cannot be seen by the driver due to occlusions by portions of the host vehicle, such as a long hood. Representatives of the U.S. Army indicate that this is indeed an issue in the field for some vehicles.

Roadways

The vehicle is assumed to be operating on a paved or unpaved "roadway," and is not operating in open terrain. A roadway is defined for the purposes of our work as a paved road or an unpaved but established motor vehicle pathway. This includes unpaved pathways that may or may not be improved, but the PSI sensing system is assumed to be capable of determining the general path that the vehicle would follow. An example of a roadway is a dirt "two-track" in a rural area. A counterexample is a footpath that does not meet this definition since it is not commonly used for motor vehicles.

Location of hazards

It is assumed that the location of relevant hazard contours with respect to the vehicle is available in two dimensions (e.g., down-range and cross-range). Furthermore, it is assumed that critical points on the edges of the hazard are available. For example, given a drainage ditch that is comprised of a negative slope that begins at the road edge and becomes more negative as the distance from the roadside increases, an ideal characterization of the hazard would include a determination of the point(s) at which the slope presents a potential rollover hazard. This would necessarily depend on the vehicle type and probable loading since, for instance, a tractor-trailer has a lower rollover threshold than a HMMWV.

It is assumed that the range and confidence at which negative-terrain hazards can be sensed and located relative to the road edge will be limited by sensor capabilities, so that warnings will sometimes occur at ranges that are less than those a system with unlimited and perfect sensing could provide. Thus in certain cases, particularly at higher speeds and with hazards that are more difficult to detect and locate, the warning will provide safety benefits for many but not all potential crash scenarios. An example is that an inattentive driver of a tractor trailer traveling at 35 m/s (77 mph) would need approximately 4 seconds or 140 m of warning to steer to avoid a hazard that intrudes 1 m into the lane. The system is not likely to be capable of warning at that range, so that a warning at 70 m would only provide two seconds to react and avoid a hazard.

Nuisance alerts

Regarding the timing of warnings, it is assumed that nuisance alerts will be a major issue due to sensing inaccuracies as well as the system's ignorance of the driver's intention to maneuver in the near future and their state of attention. The practical strategy for warning the driver of hazards is then to provide warnings only at the last moment that an avoidance maneuver is possible. It is further assumed that this "last moment" timing must accommodate a range of driver states and unknown vehicle dynamics conditions, so that the warning is only truly "last moment" for conditions that are relatively severe.

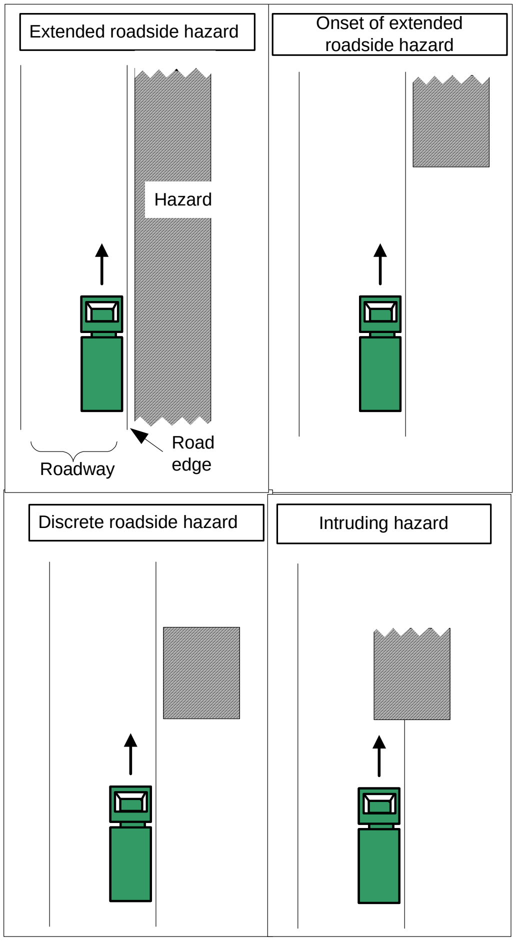


Figure 2. Four types of negative-terrain hazards that are considered

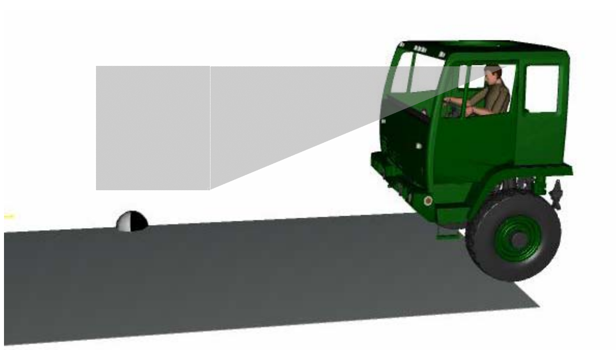


Figure 3. A discrete hazard may pass out of the driver's view at close range due to occlusions caused by the vehicle

2.2 Causality of targeted crashes

In lieu of access to crash data and subsequent analyses, the primary cause of targeted crashes for this system is assumed to be that the driver is unaware of the negative-terrain hazard soon enough to take evasive action. The driver's unawareness is further assumed to be due to inattention and/or visibility problems.

Driver inattention is considered a failure to monitor the roadway or a reduced level of monitoring relative to the driver's baseline performance with their full and wakeful attention to the road. Inattention may result from drowsiness or distraction. In this application, distraction is likely related to engagement in other non-driving, mission-related tasks. In either case, a simple descriptive model is that the driver is "out of the loop" for a period of time.

Visibility issues arise from different sources:

- Near-field visibility issues are assumed to be due to occlusion by the driver's own vehicle (determined by vehicle geometry and relationship to hazard), as well as atmospheric visibility issues and/or lack of illumination.

- Mid-field and far-field visibility issues are assumed to be due primarily to atmospheric conditions (dust, snow, fog), occlusions by other vehicles or roadway geometry (e.g., crests), or lack of illumination.

There are instances in which the combination of inattention and visibility issues may lead to crashes when only one factor would not. For example, consider lower-speed night-time operations on a minor mountain road with good atmospheric visibility and steep negative terrain hazards at the right edge of a road. The driver may be capable of seeing several seconds ahead, so that a washout of the rightmost 0.5 m of the roadbed for a short segment can be observed. But due to the distraction of other mission tasks, the driver may lose track of where the washout begins, forget about the hazard, or unknowingly drift further to the right than intended. Upon returning his or her attention to the hazard, the front of the vehicle may occlude where the hazard begins. Therefore neither inattention nor visibility alone may lead to a rollover, but a combination of those factors may.

2.3 Crash avoidance responses to system information

There are three possible vehicle-control responses when the driver decides an avoidance maneuver is necessary:

- Braking only
- Steering only
- Braking and steering

To first order, the range needed for a driver-reaction-plus-steering response is proportional to the initial vehicle speed, while the braking response is a quadratic function of vehicle speed. (See a later section for more details.) Hence the relative effectiveness of steering alone (or steering with braking) as a means of avoiding a hazard is often – but not always – better than braking alone. This is not true at very low speeds, when braking has advantages, and there are other situations in which the driver may not have sufficient information to be confident that steering is a safe maneuver.

Considering further avoidance maneuvers, the anticipated driver responses to the five types of negative-terrain hazards illustrated earlier are summarized in Table 1. Four evasive actions are shown in the table: steering to remain on the road, steering to delay road departure until after passing a discrete roadside hazard, steering to initiate a new path (avoiding an on-road hazard), and braking to rest before reaching a hazard ahead (whether off-road or on-road). The table is a simplification since steering and braking may both be involved in an evasive maneuver. Furthermore, the actual effectiveness of an evasive response to any one of the hazard types depends on many factors.

However, the simplified table makes a number of useful points. First, the nature of evasive maneuvers (and hence the timing of warnings to the driver) are related to the type of hazards. Braking may be a primary response only for certain on-road hazards. Braking will likely be a useful option for roadside hazards at very low speeds, as will be discussed later. But the scope of hazards that the system addresses (i.e., whether on-road hazards are addressed) will affect the warning timing and, in turn, the requirements on sensing ranges since braking to rest at moderate to high speeds takes much longer than steering-to-avoid maneuvers.

The table also points out that steering maneuvers may take on different forms. Steering to remain on the road is different than steering to go around an on-road hazard and will require less warning range. These statements will be supported later by discussions in the section on driver responses, and eventually by equations and simulation validation.

Table 1. Hazard types and assumed primary (1) and secondary (2) evasive responses

Hazard	Steer to maintain intended path		Steer to initiate new path	Braking
	Steer to remain on the road	Steer to delay road departure until after passing roadside hazard.	Steer around on-road hazard.	Brake to rest before reaching hazard
Extended roadside hazard	1			2
Onset of extended roadside hazard	1			2
Discrete roadside hazard	1	2		2
Intruding hazard			1	1

* Successful braking maneuvers may involve leaving the road but coming to rest before reaching the hazard.

Figure 4 shows a conceptual illustration of the range needed for different evasion maneuvers as a function of speed. Shown on this figure are some observations about two types of visibility issues – occlusions at near range that are due to the host vehicle, and visibility issues at longer ranges due to atmospheric conditions or illumination. Please note that this figure is inaccurate in its depictions of the relative range at which steering, braking, and normal road preview are required, but is useful to illustrate that, for example, occlusion by the host vehicle is an issue that can be addressed only at low speeds, or by making the driver aware of the hazard at an earlier time. The figure also shows that vision issues related to atmospheric visibility and illumination are more pressing problems at higher vehicle speeds.

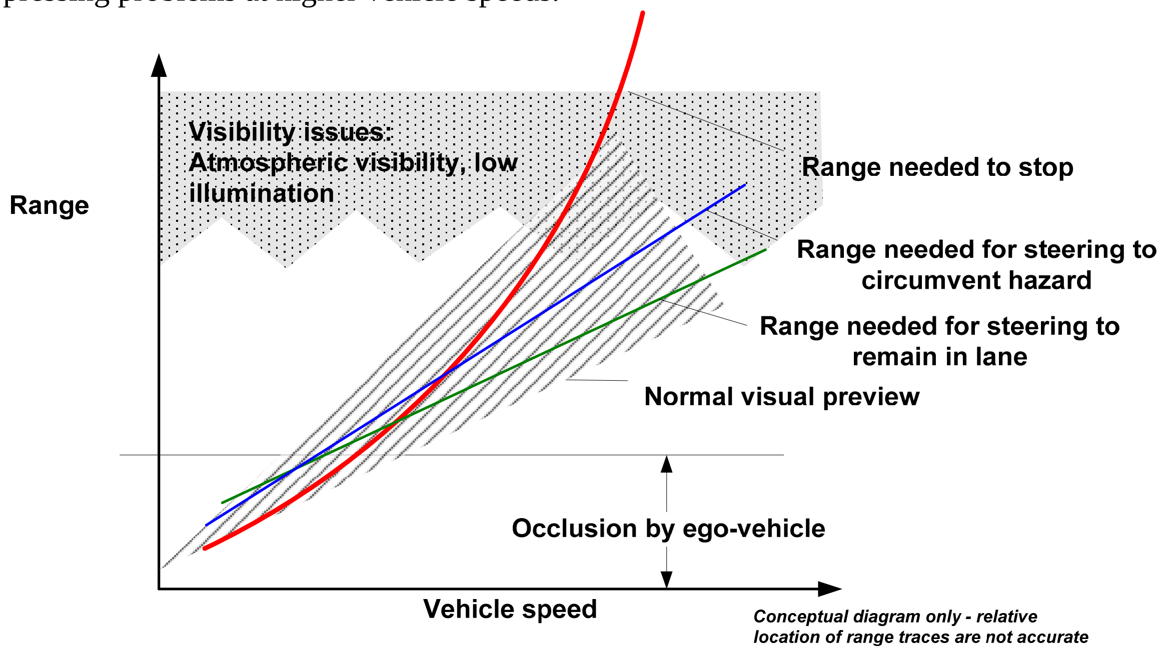


Figure 4. Conceptual overlaying of visibility issues with warning ranges needed to avoid hazards by steering or braking

The combined ability of the vehicle and the driver to execute a stable evasive maneuver should be considered in setting warning algorithm parameters. Since it is infeasible to detect and account for individual driver capabilities, the primary factor becomes the vehicle and general assumptions about driver responses. The following are some of the factors that will affect the stability and effectiveness of braking and/or steering maneuvers:

In general, factors that influence effective evasive maneuvers include, but are not limited to:

- Vehicle speed
- Vehicle rollover threshold (e.g., static rollover threshold)
- Vehicle roll stability
- Handling and braking capability of the vehicle system
- Road surface characteristics, especially friction, roll-tripping elements, loose surface, etc.,

- The driver's perception of the roadway beyond the hazard (for considering possibly negative, secondary effects of an evasion)
- Oncoming traffic (not considered in this work)
- Possible negative impacts of steering and/or braking maneuvers on other crew members, vehicle elements, and onboard cargo or hardware
- Proximity of following vehicles.

Many of these factors cannot be taken into account in real time because measurements or estimates are not available. Nevertheless, these factors may influence higher-level decisions about what the real-time algorithms should seek to achieve. For example, in the civilian domain, steering is not considered a reasonable assumption for an inattentive driver who receives a warning for a discrete, intruding hazard. This is true because there are too many possible negative effects of a sudden lane change or swerve by an inattentive driver in that application, since experiments have shown that drivers are reluctant to make steering maneuvers in surprise rear-end crash situations. Thus the bulleted factors above may influence the system, but most will not be available in real time.

The comments below address selected items within the above bullet list. A later section addresses the availability of estimates of these and other variables.

- **Vehicle effects:** It will be important to capture some aspects of the vehicle type and its likely configuration in parameters that are used in warning decisions algorithms. This will include rollover threshold estimates as well as handling and braking capabilities.

- **Road surface effects:** Road surface effects may constrain braking levels and handling maneuvers that are supportable by the driving surface. Tripped rollover considerations are also appropriate to consider.[1] The most important item is likely to be whether the road is paved or not. This may not be available, however.

- **Road geometry effects:** Road curvature influences the effectiveness of avoidance maneuvering. In general, when compared to a straight road segment, a hazard in a curve will be harder to evade when the curvature is such that the hazard is on the "outside" of the curve (e.g., a hazard on the right of the lane when curvature is to the left). Conversely, evasion is more effective than even a straight road segment when the hazard is on the "inside" of the curve (e.g., a hazard on the right of the lane when curvature is to the right). This will be true for braking and is especially true for steering.

The current document addresses basic vehicle effects and road geometry effects in the following manner. Vehicles are first assumed to be two-axis vehicles and not tractor trailer vehicles or other multi-axis vehicles with or without trailers. Second, road curvature and path curvatures are considered in detail, although the effects of grade are

[1] Assume that wetness or muddiness of a road is not observable or available. Wetness or muddiness (or snowiness) is often due to precipitation that occurred hours or days beforehand, and spring thawing often creates low friction conditions on sunny days.

not accounted for in terms of the timing of warning drivers. Finally, road surface effects are not addressed. This and many other considerations that are likely to be significant in the field are beyond the scope of this initial effort.

3 Driver-vehicle interface concepts

The driver-vehicle interface (DVI) for the intended system is based on the system goals and assumptions that were described in Section 2. More specifically, the objectives of the DVI are to (1) warn the driver of an oncoming hazard in the driver's future path, (2) provide the warning in a timely manner, sufficiently early to allow for a reasonable avoidance response, and (3) when appropriate, inform the driver of a possible response, including alternative options that could be used to avoid the hazard.

The role of the countermeasure in assisting the driver to avoid negative-terrain hazards will depend on the scenario, and especially on the driver's state and the visibility of the roadside hazards. Among the roles that the countermeasure may play are the following:

a) Provide complementary information for the driver's vision in poor visibility situations (especially near-field)
b) Provide a "copilot's" reminder of an upcoming hazard that can be perceived by the driver
c) Provide a copilot's convenient and continual "packaging" of information about the roadway including hazards and the relative direction to be maintained – useful for simplifying a heavily tasked driver
d) Warn the driver to return their attention to the driving task, especially when the driver is inattentive or drowsy.
e) Provide advisory information on an on-demand basis so that it is not interfering with normal operation but is available when needed.
f) As the system has no knowledge of the state of the driver, there may be nuisance alarms that result from the system's assumptions about the driver's attentiveness. The countermeasure will have some level of adjustment to account for this by allowing an attentive driver to disable, or mute, the system to reduce undesired annoyance.

3.1 Human factors considerations

The main Human Factors considerations in the decision about an optimal DVI appear below. (This is a selected subset of issues raised in Campbell et al., 2007.) Decisions about addressing these questions in the intended application are based on input from UMTRI and PSI.

1. What is the number of warning stages: Imminent warning only, or cautionary warning(s) followed by an imminent warning?
2. What is the best way to make warnings compatible with expected driver responses?
3. How to prevent false or nuisance warnings?
4. What is the optimal timing of warnings? Generally speaking, response time to a warning is on the order of 1 s.

5. What is the preferred modality of the warning? (consideration of auditory, visual, and haptic)
6. What are the main characteristics of the warning signal? (e.g., conspicuous, distinguishable, conveys meaning and urgency, , not annoying, etc.)
7. Driver control (adjustments) for system sensitivity and behavior.

Table 2 uses the following terms to describe the role of information provided:

- Driver support: Support visibility (e.g., continual displays of steering direction or hazard location that the driver may decide to consult)
- Guidance: Guide driver (e.g., continual displays of steering direction or hazard location that the driver must consult)
- Warnings: Warn driver when necessary to enable an inattentive driver to return attention to the driving task (e.g., momentary audio tone) or to notice an upcoming hazard (e.g., audio tone with overlay on a continual display).

Table 2. Levels of information conveyed to the driver

	Visibility		
Driver state	Good visibility (except blind spots)	Poor visibility far ahead (e.g., 4 sec ahead)	Poor visibility near (e.g., 1 sec ahead)
Attentive	No imminent action needed Cover blind spots visually or provide supplement information	Hazard alerts	Continual driver support with warnings for specific hazards
Attentive with lapses, or inattentive	Hazard alert to prompt attentiveness (preferred auditory and/or Haptic)	Hazard alerts It is possible to convey desired response in the alert (e.g., swerve left/right)	Continual driver support with warnings *We assume that it is likely a driver will be attentive when near visibility is poor.

3.2 Candidate driver interface approaches

Three DVI approaches are considered below based on our analysis of human factors needs for the system. The approaches are all plausible, but differ in their intended purpose and expected effectiveness for various scenarios.

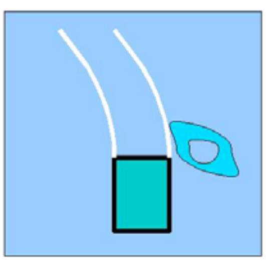
Option 1: A single auditory alert with lateral (left/right) distinction

Lateralized auditory alert when a negative terrain (low speed) or a lane departure (high speed) is detected. The alert is similar to existing civilian applications of Lane Departure Warning (LDW) (e.g., see LeBlanc et. al, 2006.) The auditory component is lateralized so that it is heard on the left when the danger is on the left and on the right when the danger is on the right. A haptic component could be added as a lateralized seat shaker. A visual component is not recommended in this option. This solution best applies to high-speed, known-path driving but could work in off-road situations. Regarding the list of Human Factors considerations in the introduction to this section, the preferred modality here is auditory. .

Other issues or features of this option are:

- It is assumed that speakers can be added to the vehicle, and preferrably speakers to allow lateralization of the alert (right-side hazard leads to an auditory alert on the driver's right side)
- It is assumed that there is not a technical feasibility of a haptic solution in the presence of high vibration, especially on unpaved roads.
- The issue of annoyance and false alarms is center to the decision about using auditory alerts. Acceptance is heavily related to the level of perceived annoyance.
- The auditory alert solution is an accepted solution in current and near-future civilian solutions and should be explored seriously for this system if civilian transportation is of interest for this product.

Option 2: Map-view visual display with hazard information

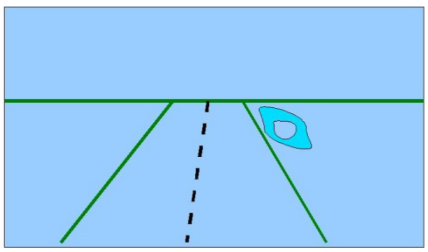


A map view (or birds-eye view) visual display indicates at a minimum the position of the hazard area and current position of vehicle relative to the expected future path of the vehicle. This solution is primarily geared toward off-the-road driving where the future path of the vehicle is not entirely clear, and the driver can choose to change the path in the presence of the indicated danger. This solution is also geared toward low speed driving in which the driver may already be aware of the hazard, and the map view is used by the driver during maneuvering. The display is likely to be helpful when visibility is low (e.g., night time, no headlights, fog, rain).

Visual is the preferred modality to present spatial information. In terms of the Human Factors considerations, this option involves a continuous display of advisory information. We do not suggest relying on a visual display *only* for warnings, so the visual information is only for advisory information when the driver is already known to be looking at the display. When a warning is required, the auditory cue is best (see option 1 above). The presentation of visual information should consider time lag in the display presentation and interpretation; excessive latencies may undermine the utility of this approach.

A visual display requires looking away from the road and is therefore not generally the desired solution for a warning system. It is preferred that the information would be conveyed to the driver on an on-demand basis for expected events and other solutions be proposed for alerting the driver of an unexpected situation.

Option 3: Driver-view visual display with overlaid highlighting of hazard ahead



The driver-view option assumes that a night vision system or some other camera view system is installed and available in the vehicle. The camera view is displayed to the driver (possibly on-demand only) and is overlaid with information about the location of danger areas ahead. This solution differs from the map-view solution in that the display is likely to be used when visibility is low and could be combined with a night vision system.

The Human Factors considerations are similar to option 2.

3.3 Recommended driver-vehicle interface concept

Based on our analysis and discussions of the technical assumptions and limitations with project partners, the recommended concept for driver interface is a combination of the first and third approaches above..

1) Visual and auditory display capabilities:

   a) Auditory alert

      - The system will have the capability to play a wav file as an auditory alert with a lateral (left/right) component.
        (UMTRI can provide reference to results from the IVBSS experiments on tones for lane departure for light vehicles and for trucks.)

      - An auditory alert will be presented only once for any given hazardous area.

- Note that often a hazard will be displayed for some time before the auditory alert occurs.   At other times, the hazard will appear on the screen at the same time as the occurrence of the auditory alert.

b) A visual color display, with at least an on/off switch, but preferably an implemented logic for automatic on and off as a function of the vehicle speed and other environment factors. The display will consist of:

- A driver's view video (regular camera view or night vision view) of forward scene, plus
- overlay of significant negative-terrain hazards when appropriate, plus
- sensor coverage area, including area already scanned (e.g., triangle showing maximum range and azimuthal scan), plus
- vehicle path prediction indicated as an "arc" overlaid on the image

2) Overlay of hazards on the display

a) Determining when overlays are available, i.e., higher-level decision regarding whether system is in the mode to present this information:

- Manual: overlays are shown based on driver selection (see driver controls below)
- Automatic: alternative to a driver-controlled mode switch: Visual overlay of hazard is activated in all conditions, unless the speed exceeds 45 mph or the visibility is "good," as indicated by a vision-based sensing of ambient illumination and consideration of LIDAR backscatter.

b) Ongoing determination of which hazards should have overlays associated with them:

- See threat assessment. This depends on hazard location, speed, and yaw rate.

c) How to overlay hazard areas: White "X" at the nearest corner of the hazard (details TBD)

d) Overlaying vehicle path: White "arc" shows the yaw-rate-based path ahead. This overlay is activated only when a hazard area is highlighted on the display and presents the driver with an easy way to confirm the intention of the system alert.

e) Upon presenting an auditory alert, the visual overlay associated with that hazard may be highlighted briefly (e.g., 5 seconds)

3) Driver controls:

a) Three-position "switch"

- System off;
- Auditory alerts enabled;
- Auditory alerts and Display enabled

b) Volume level control with a range that is adjusted to the vehicle noise characteristics. As a default, about 80 db at the driver's ears is desired.

4) System status information

- System status indicator implemented as an LED or other visual, as shown below.

Table 3. Indications of system staste to the driver

System state	Indication to driver
Off (determined by driver control)	None
Not operating – basic operating conditions not appropriate: e.g., speed too low	Fault indicator on (e.g., red LED): the system is not operating
Not operating – low confidence or fault state	Fault indicator on (e.g., red LED): the system has low confidence. Consider threshold to prevent flicker of the indicator
Operating – auditory alerts enabled	System availability Indicator (e.g., green LED) the system is on.
Operating – auditory alerts and display enabled	Triangle on overlay showing coverage zone

4 Path prediction

Path prediction is the real-time computation of the expected future location of the vehicle. This is useful for determining whether the vehicle appear to be headed for an encounter with a perceived negative-terrain hazard. Uncertainties which affect the accuracy of the prediction include measurement uncertainties and uncertainties in the model used to compute the future path model. One of the most important uncertainties involves the path model's necessary assumptions about the steering or braking action that the driver may take in the near future.

Two subsections follow – the first addresses definitions and assumptions, and the second presents equations for predicting the vehicle path based on a steady-state cornering model.

4.1 Definitions and assumptions

Vehicle coordinate system:

The International Standards Organization (ISO) convention for vehicle-fixed coordinate systems is used, with the x axis pointing forward along the vehicle centerline, the y axis laterally out the left side of the vehicle (driver's side in the US configuration), and the z axis vertical away from the earth.

To define the origin of the vehicle-fixed coordinate system used in this document, begin with a point at or near the sensor location, then translate that point to the centerline of the vehicle (along the longitudinal (x) axis). The vertical (z) location of the origin need not be defined for these equations. This is because roll & pitch effects are not significant for the purposes of these equations. (These effects are very significant for the sensor-to-vehicle-coordinates transformation, and the projection of sensor coordinates onto the terrain, but that is outside the scope of this memo.)

Measurements

Two basic measurements are critical to the system – yaw rate, r, and vehicle speed. Because of the specific application addressed in this project, and because of the aftermarket nature of the system and its intended implementation across many types of vehicles, these will be the only two measurements available, except for the location of negative-terrain hazards.

Two forms of vehicle speed are relevant: the magnitude of the velocity vector at the origin of the coordinate system, V, and the forward vehicle speed, which is generally defined as the component of the velocity vector measured along the x axis, u. In practice, V and u can be assumed to be equal and may be measured using speed signals provided by the vehicle (u) or speed collected from a GPS unit (V). The equations below use the proper type of vehicle speed (u or V), but under the operating assumptions that are interchangeable.

Appendix A addresses practical considerations for the use of GPS for vehicle speed. Yaw rate should come from a dedicated yaw rate sensor; Appendix A addresses the potential and challenges of using GPS to compute yaw rate.

The path prediction equations and the threat assessment algorithms that are developed later in this section or in Section 5 require the ratio of two vehicle parameters, $(m_r / C_{\alpha r})$, where

m_r effective mass on the rear axle

$C_{\alpha r}$ cornering stiffness of the rear axle, e.g., N/rad

In practice, the values of m_r and $C_{\alpha r}$ will be poorly known in the field. For the purposes of engineering development, UMTRI can provide reasonable estimates for this ratio if the following values are provided:

- Vehicle type
- Curb weight (unloaded), gross vehicle weight rating (with maximum load allowed), and typical loading of vehicle
- Tire size (e.g., "P205/50R15"), and number of tires per axle

Operating conditions

The vehicle speeds to be considered are assumed to be between 5 and 30 m/sec. The maximum sensor range is assumed to be 60 m, with an azimuthal sweep of plus or minus 30 degrees. These assumptions on speed and sensor coverage lead to upper and lower bounds on path radii to be considered. Furthermore, it can be assumed that at the time of an alert, vehicle will not be traveling so as to create levels of lateral acceleration that are well above normal levels expected in the field. A limit of 0.4 g is assumed to be reasonable for larger vehicles with two or more axles.

4.2 Vehicle path prediction

This section presents equations for predicting the future location of the vehicle – specifically, the origin of the vehicle-fixed coordinate system – based on estimates of the current speed *u* and yaw rate *r*. Note that explicitly predicting path is optional for a warning system – the expressions provided in Section 5 on threat assessment could be used to leave much of the relationships in this section moot.

Steady-state cornering and sideslip angle

In the field, there will be no information about the steer angle, accelerations, or even the actual rotational inertial properties of the vehicle. This leaves us with the need to assume that the vehicle is either traveling perfectly straight ahead or – much more commonly – is following a circular arc. The latter case is termed steady-state cornering and will apply here when the measured or estimated yaw rate is nonzero. The radius of the arc will be simply

$$R = \frac{u}{r} \ . \tag{1}$$

It is well known that body sideslip occurs in steady state cornering. Body sideslip is the difference between the direction of travel (velocity vector) and the vehicle *x* axis, as shown in Figure 5. Sideslip is important to consider since the sensor-to-vehicle transformation will reconcile the sensor information with the vehicle axis, but then it needs to be further reconciled with the motion of the vehicle. The body sideslip angle varies along the length of the vehicle. For typical motions and the operating condition assumptions , body sideslip will be less than a few degrees, and more typically less than half a degree. These amounts can be significant at higher speeds since, for instance, when traveling at 20 m/sec (45 mph), an error in sideslip of 0.5 deg is equivalent to 0.5 m of error in the predicted position of the vehicle at a time 3 sec into the future (60 m).

At a point that is a distance *b* ahead of the rear axle, the sideslip angle β is proportional to the yaw rate, and can be written as [1]:

$$\beta = \frac{b}{R} - \frac{m_r}{C_{\alpha r}} \cdot \frac{V^2}{R} = r\left(\frac{b}{u} - (\frac{m_r}{C_{ar}})(\frac{u}{\cos^2 \beta})\right) \approx r\left(\frac{b}{u} - (\frac{m_r}{C_{ar}})u\right) \tag{2}$$

u forward speed, m/s
V speed along the velocity vector, m/s
b longitudinal distance from PSI sensor location to rear axle, m
m_r effective mass on rear axle (F_z/g on rear axle), Kg
$C_{\alpha r}$ rear axle cornering stiffness, N/rad
r yaw rate, rad/s (positive when vehicle is rotating about the positive z-axis, i.e., counterclockwise, as viewed from above)

At low speeds, the first term of the equation above dominates, so that the sideslip angle for any point in front of the rear axle ($b>0$) has the same sign than the sign of yaw rate. This means the rear wheels track further inboard than the front wheels. Figure 5 is an example of this situation, with the counter-clockwise arc (positive yaw rate) resulting in a positive sideslip angle.

At higher speeds, the sideslip angle and the yaw rate have different signs. At these higher speeds, the rear wheels are tracking further outboard. For a positive yaw rate (counter-clockwise rotation), sideslip becomes negative at higher speeds.

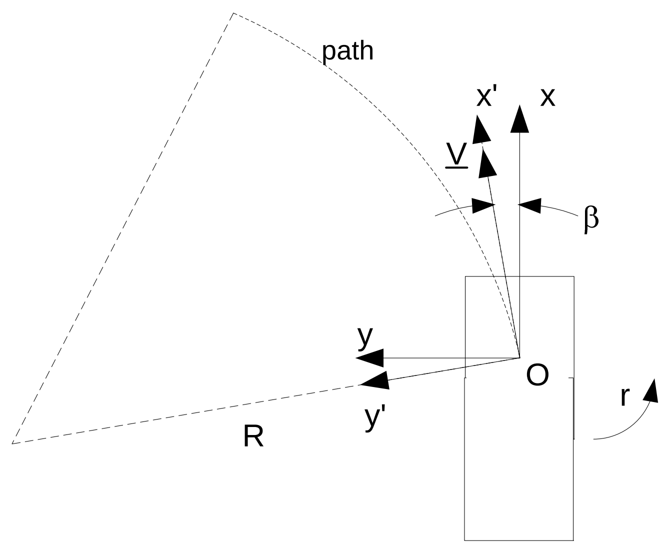


Figure 5. Motion of a vehicle in steady state cornering (low-speed case shown)

Path in vehicle-based coordinates

In steady-state cornering, the path of the origin O of the vehicle coordinate system will follow an arc. The arc will be tangent to the velocity vector $\underline{\boldsymbol{V}}$ and will have a radius of curvature of $R = u / r$, as shown in Figure 5. The predicted path in vehicle coordinates (*x*,*y*) are desired, where (*x*,*y*) were introduced in the first section of this document.

For convenience, consider also *(x’, y’)*, another vehicle-fixed coordinate system with the same origin as (x,y), but with x’ aligned with the current velocity vector and y’ orthogonal to x’ (such that z’ and z both point vertically upward). That is, (*x’*, *y’*) would apply if there was no body sideslip angle.

For ideal straight-line driving with no yaw rate, the sideslip angle β is zero, and (x,y) and (x’,y’) are identical. Therefore the predicted path is:

$$\begin{aligned} x(t) &= ut \\ y(t) &= 0 \end{aligned} \qquad (3)$$

For steady-state cornering, however, the future path of point O will follow an arc, and in the (*x’*, *y’*) coordinates, will be:

$$x'(t) = R\sin(rt) = \frac{u}{r}\sin(rt)$$

$$y'(t) = R(1-\cos(rt)) = \frac{u}{r}(1-\cos(rt))$$

This can be transformed into (x,y) coordinates as follows:

$$x(t) = x'(t)\cos\beta - y'(t)\sin\beta$$

$$y(t) = x'(t)\sin\beta + y'(t)\cos\beta$$

so that

$$\begin{aligned} x(t) &= \frac{u}{r}(\sin(\beta + rt) - \sin(\beta)) \approx ut, \quad \textit{and} \\ y(t) &= -\frac{u}{r}(\cos(\beta + rt) - \cos(\beta)) \end{aligned} \qquad (4)$$

The above equations is probably the most practical expression for path prediction. Recall that these expressions are for steady-state cornering, and when yaw rate becomes close to zero, the straight-line driving expressions developed earlier must be used.

4.3 Uncertainty in path prediction

Errors in path prediction will be due to several factors, including:

1. the errors in measuring speed (u) and yaw rate (r),
2. error in the assumption that speed and yaw rate remain constant over the time period *T*,
3. error in the assumptions of a flat road,
4. error in the assumed values of rear-axle mass and cornering stiffness, and

5. errors in the use of the so-called "bicycle" model that describes steady state cornering for two-axis vehicles, and especially errors that may result at lower speeds and small curve radii.

This memo treats only the first error, i.e., errors in measuring speed and yaw rate. In order to treat the remaining errors in a standard manner, the path prediction and path uncertainty would need to be computed recursively in the real-time system, so that the resulting computations would consist of a real-time numerical integration to predict the future path, and an associated integration to compute a covariance matrix.

The path prediction expressions address two cases: when the nominal yaw rate is non-zero (steady-state cornering assumed), and when the yaw rate is zero or very close to zero (straight-line driving). The uncertainty developed here is the covariance matrix associated with the predicted position (*x*,*y*), where again the position is estimated relative to the current position at t=0, and expressed in the coordinate frame as it is oriented at t=0.

Define Δu and Δr as the measurement errors in speed and yaw rate, respectively, such that the true speed u and the true yaw rate r at time t =0 can be written as a function of the measured values u_m and r_m .

$$u_m = u + \Delta u$$
$$r_m = r + \Delta r$$

Let the errors in speed and yaw rate be mutually independent and zero mean. Thus the variances in the predicted position (*x*,*y*) can be approximated by using the first order terms in a Taylor series expansion of (*x*,*y*) with respect to u and r :

$$\begin{aligned} {\sigma_{xx}}^2 &= S_{x,u}^2 \ {\sigma_u}^2 + S_{x,r}^2 \ {\sigma_r}^2 \\ {\sigma_{yy}}^2 &= S_{y,u}^2 \ {\sigma_u}^2 + S_{y,r}^2 \ {\sigma_r}^2 \\ {\sigma_{xy}}^2 &= S_{x,u} S_{y,u} {\sigma_u}^2 + S_{x,r} S_{y,r} \ {\sigma_r}^2 \end{aligned} \tag{12}$$

where the sensitivity variables $S_{a,b}$ denote the partial derivative of *a* with respect to *b*, evaluated at the conditions at the start of the prediction. Therefore the covariance matrix for the predicted position (*x*,*y*) is

$$Cov(x,y) = \begin{bmatrix} {\sigma_{xx}}^2 & {\sigma_{xy}}^2 \\ {\sigma_{xy}}^2 & {\sigma_{yy}}^2 \end{bmatrix}. \tag{13}$$

The values for S are derived in Appendix B, and are a function of r, u, and the prediction interval T.

For yaw rate near zero. When the yaw rate is zero or is very close to zero (e.g., with a magnitude less than 0.002 radian/sec), the assumption of travel on a circular arc does not hold and computations using expressions based on circular arcs will be unstable. In the case of zero or almost-zero yaw rates, the predicted location of the origin of the vehicle-fixed coordinate system at a time T in the future is given by equation (3). Those expressions, however, are not useful for developing the sensitivity to errors in yaw rate or speed because they do not include effects of curvature. A pair of equations that are suitable for an approximate prediction of path at very small yaw rates are:

$$\begin{aligned} x(T) &= uT \cdot \cos(\frac{rT}{2}) \\ y(T) &= uT \cdot \sin(\frac{rT}{2}) \end{aligned} \tag{14}$$

Therefore the sensitivities to errors in speed u and yaw rate r (which are defined by the first-order partial derivatives, evaluated at the nominal value of u and r=0) are:

$$\begin{aligned} S_{x,u} &= \frac{\partial x}{\partial u} &&= T\cos(\frac{rT}{2}) = T \\ S_{x,r} &= \frac{\partial x}{\partial r} &&= -\frac{1}{2}uT^2 \cdot \sin(\frac{rT}{2}) = 0 \\ S_{y,u} &= \frac{\partial y}{\partial u} &&= T\sin(\frac{rT}{2}) = 0 \\ S_{y,r} &= \frac{\partial x}{\partial r} &&= \frac{1}{2}uT^2 \cdot \cos(\frac{rT}{2}) = \frac{1}{2}uT^2 \end{aligned} \tag{15}$$

The uncertainty in the path of equation (14) is then expressed as a covariance matrix (equation (13)) with elements that are defined in equation (12). For clarity,

$$\sigma_{xx}{}^2 = S_{x,u}{}^2 \cdot \sigma_u{}^2 + S_{x,r} \cdot 2\sigma_r{}^2 = T^2 \cdot \sigma_u{}^2$$

$$\sigma_{yy}{}^2 = S_{y,u}{}^2 \cdot \sigma_u{}^2 + S_{y,r} \cdot 2\sigma_r{}^2 = \frac{1}{4}u^2T^4 \cdot \sigma_r{}^2$$

$$\sigma_{xy}{}^2 = S_{x,u}\ S_{y,u} \cdot \sigma_u{}^2 + S_{x,r}\ S_{y,r} \cdot \sigma_r{}^2 = 0$$

For non-zero yaw rate (steady-state cornering). The sensitivity of the predicted path will again depend on the speed u and yaw rate r. It is useful to first present some useful intermediate steps, including the partial derivative of the sideslip angle β by speed and yaw rate:

$$\begin{aligned} \frac{\partial \beta}{\partial u} &= \frac{-br}{u^2} - \frac{m_r}{C_{\alpha r}} r \\ &\quad -r \cdot (\frac{b}{u^2} + \frac{m_r}{C_{\alpha r}}) \\ \frac{\partial \beta}{\partial r} &= \frac{\beta}{r}\ . \end{aligned}$$

It is also useful to recall the basic rules for partial derivatives of sines and cosines:

$$\frac{\partial \cos f(\theta)}{\partial \theta} = \frac{\partial f(\theta)}{\partial \theta} \cdot (-\sin f(\theta))$$

$$\frac{\partial \sin f(\theta)}{\partial \theta} = \frac{\partial f(\theta)}{\partial \theta} \cdot (\cos f(\theta))$$

so that the following expressions can be derived to support later developments:

$$\frac{\partial \sin(\beta + rt)}{\partial u} = \frac{\partial(\beta + rt)}{\partial u} \cdot \cos(\beta + rt) = [\frac{-br}{u^2} - \frac{m_r}{C_{\alpha r}} r] \cdot \cos(\beta + rt)$$

$$\frac{\partial \sin(\beta + rt)}{\partial r} = \frac{\partial(\beta + rt)}{\partial r} \cdot \cos(\beta + rt) = (\frac{\partial \beta}{\partial r} + t) \cdot \cos(\beta + rt) = (\frac{\beta}{r} + t) \cdot \cos(\beta + rt)$$

The sensitivities of *x* to changes in speed *u* and yaw rate *r* are derived by using the chain rule on equation (10) for the curved path case:

$$\begin{aligned} S_{x,u} = \frac{\partial x}{\partial u} &= \frac{1}{r}(\sin(\beta + rT) - \sin(\beta)) + \frac{u}{r}(\cos(\beta + rT) - \cos(\beta)) \cdot \frac{\partial \beta}{\partial u} \\ &= \frac{x(T)}{u} - y(T) \cdot \frac{\partial \beta}{\partial u} \\ &= \frac{x(T)}{u} + r \cdot y(T) \cdot [\frac{br}{u^2} + \frac{m_r}{C_{\alpha r}}] \\ &\approx t - r \cdot y(T) \cdot [\frac{b}{u^2} + \frac{mr}{C_{\alpha r}}] \end{aligned} \tag{16}$$

$$\begin{aligned} S_{x,r} = \frac{\partial x}{\partial r} &= -\frac{u}{r^2}(\sin(\beta + rT) - \sin(\beta)) + \frac{u}{r}(\cos(\beta + rT) \\ &\quad - \cos(\beta)) \cdot (\frac{\partial \beta}{\partial r} + T) \\ &= -\frac{x(T)}{r} - y(T) \cdot (\frac{\beta}{r} + T) \\ &= \frac{x(T)}{r} - y(T) \cdot [\frac{b}{u} - \frac{m_r}{Cr} u + T] \end{aligned} \tag{17}$$

The expression for $S_{x,u}$ shows that the sensitivity of errors in predicting the *x* component has two terms, the first of which simply shows that the error in *x* grows linearly with time. This first term describes the simple effect that speed errors integrate with time. The second term comes from both the impact of speed on the sideslip angle and as well as its impact on the radius of curvature.

The expression for $S_{x,r}$ also has two terms.

The sensitivities of y to changes in speed u and yaw rate r are derived in a manner similar to those developed earlier for x . These are shown below.

$$
\begin{aligned}
S_{y,u} \quad = \frac{\partial y}{\partial u} \quad &= -\frac{1}{r}(\cos(\beta + rT) - \cos(\beta)) + \frac{u}{r}(\sin(\beta + rT) - \sin(\beta)) \cdot \frac{\partial \beta}{\partial u} \\
&= \frac{y(T)}{u} + x \cdot \frac{\partial \beta}{\partial u} \\
&= \frac{y}{u} + x(T) \cdot [-\frac{br}{u^2} - \frac{m_r}{C_{\alpha r}} r] \\
&= \frac{y(T)}{u} - r \cdot x(T) \cdot [\frac{b}{u^2} + \frac{m_r}{C_{\alpha r}}]
\end{aligned}
\tag{18}
$$

and

$$
\begin{aligned}
S_{y,r} \quad = \frac{\partial y}{\partial r} \quad &= \frac{u}{r^2}(\cos(\beta + rT) - \cos(\beta)) + \frac{u}{r}(\sin(\beta + rT)(\frac{\partial \beta}{\partial r} + T) \\
&\qquad - \sin(\beta) \cdot \frac{\partial \beta}{\partial r}) \\
&= -\frac{y(T)}{r} + x(T) \cdot \frac{\partial \beta}{\partial r} + \frac{uT}{r} \sin(\beta + rT) \\
&= -\frac{y(T)}{r} + x(T) \cdot \frac{\beta}{r} + \frac{uT}{r} \sin(\beta + rT)
\end{aligned}
\tag{19}
$$

The errors in the prediction of (x,y) can be computed using equations (12), (13), and those directly above.

5 Threat assessment

Threat assessment consists of real-time algorithms that determine whether driver information should be presented. Two rules for when to present auditory alerts are presented below; these comprise a first set of threat assessment approaches and algorithm sets. The first rule is that a warning should be presented if the driver must instantaneously change the lateral acceleration by a certain amount in order to avoid a negative-terrain hazard. The second rule is that a warning should be provided if the driver, after a short reaction time, must apply a step change in deceleration in order to stop before a hazard.

The rule of thumb in the passenger vehicle market for highway vehicles in the US and Europe has been to assume the driver will use steering maneuvers for most lateral threats (run-off-road), and braking for forward threats (rear-end crash scenarios). But for the latter, it is also true that warnings for forward threats are timed to strike a compromise between maximum safety benefit (timely warnings) and reducing annoyance that comes when the driver is attentive and intending to steer around the vehicle ahead, or when the driver is anticipating the lead vehicle will leave the lane.

This comment is relevant for the current problem because alert and attentive drivers will often be intending to begin a maneuver when a conservative warning is provided. Thus it is likely in the soldier's interests to delay warnings as long as possible, and delay alerts when any evidence of driver attention is noted, e.g., steering rate or longitudinal accelerations.

A high-level warning rule set is suggested:

1. Warn when there is neither sufficient distance (at current speeds) to steer around the hazard using a moderate steering maneuver, nor distance to brake to a stop before the hazard using moderate braking.

2. If there is any evidence of a safety-positive change in the path direction or application of braking, delay the alert until there is neither sufficient distance to steer around the hazard using a strong steering maneuver, nor distance to brake to a stop before the hazard using strong braking.

    Path direction change: If change in yaw rate is more than 5 deg/sec^2.

    Application of braking: If the absolute value of deceleration is greater than 1 m/sec^2.

3. Do not issue warnings if the time to collision is less than 5 seconds. (This reflects a desire to reduce false alerts that occur when drivers are attentive but have not yet begun a steering or braking maneuver.)

4. Require that the threat assessment criteria is met for 0.3 seconds.

5. Require that the vehicle operating speed is between 3 and 30 m/sec.

The computation of the distances referred to in the first two items are now addressed in turn.

Threat assessment with braking as an evasive maneuver

A basic rule is proposed to consider hazard avoidance through driver braking in order to bring the vehicle to rest just at the identified hazard location:

> Warn the driver if the distance to a hazard equals the vehicle stopping distance plus the distance traveled during a short driver reaction time.

Assume that the response to such a warning involves a period of constant speed travel (for duration *RT*), followed by a step change in acceleration of $\Delta a_x *$, relative to ongoing acceleration, where $\Delta a_x *$ is negative for additional deceleration. Assume the current vehicle speed along the longitudinal axis is denoted u and the current acceleration is a_x (negative for braking). Then the warning should be issued at a distance d where

$$d = u \cdot RT + \frac{1}{2} a_x \, RT^2 + \frac{(u + a_x \cdot RT)^2}{-2(a_x + \Delta a_x *)} \ .$$

Parameters to use:

> $\Delta a_x *$ -2.5 m/s^2 when $a_x > -1.0 m/\sec^2$ (driver not braking significantly) and -1.5 m/s2 when $a_x \le -1.0 m/\sec^2$ (driver is braking)
>
> RT 0.7 s when $a_x > -1.0 m/\sec^2$ (driver not braking significantly) and 0.25 sec when $a_x \le -1.0 m/\sec^2$ currently, or within the last 3 seconds (significant driver braking assumed to signal attentiveness to hazards)

The variation of RT above is very useful in practice.

Threat assessment for steering as an evasive maneuver

A basic rule is proposed to consider hazard avoidance through driver steering :

> Warn the driver if avoiding a hazard requires an instantaneous step change in lateral acceleration that exceeds a threshold. The new lateral acceleration is assumed to be applied throughout the remainder of the path prediction period.

Thus, if the lateral acceleration required to avoid the hazard differs from the current value of lateral acceleration by more than the threshold value, a warning should be considered.

Since hazards are not points but regions, it is assumed that two points are defined per hazard – a leftmost point, P_L and a rightmost point, P_R, as seen from the vehicle. Define a_y as the current lateral acceleration (positive when yaw rate is positive), $a_{y,L}$ as the value of lateral acceleration that would result in the path of the vehicle intersecting the leftmost point, and $a_{y,R}$ as the value associated with a steady-state path intersecting with the rightmost point. Define also the threshold for the change in lateral acceleration, $\Delta a^* > 0$. Then for that hazard, the basic warning rule is:

$$\text{Warn if } (a_{y,R} - \Delta a_y^*) \leq a_y \leq (a_{y,L} + \Delta a_y^*) \tag{3}$$

<u>Threshold value,</u> Δa_y^*

Value for threshold: A first suggestion is that $\Delta a_y^* = 2$ m/s^2.

The specific relationships derived in this document will yield relatively "late" warnings, but a simple adjustment to the threshold can produce a more conservative warning system. These relationships are described as "late" because the system is only allowing the driver enough distance to avoid the hazard through a single step change in lateral acceleration. That means that when the vehicle has traveled far enough down-range to reach the hazard, the vehicle will have significant speed laterally which must presumably be removed – probably by lateral acceleration in the opposite direction – once the critical point of the hazard is passed. This leads to overshoot in the lateral direction that will require a safe-travel zone of approximately the same lateral distance as that consumed in the avoidance maneuver– and there may or may not be sufficient room for that.

A more conservative approach would be to provide warnings with enough distance to both avoid the obstacle and return the vehicle path to a direction parallel to the initial curved path by the time the hazard is reached. This would require exactly twice the distance, if one assumes this is accomplished by two step inputs of lateral acceleration in sequence– the first to avoid the hazard (e.g., to the left), and the second to return the vehicle to a forward direction (e.g., lateral acceleration to the right). This approach can be effected simply by using a threshold Δa_y^* which is half the value suggested here. This, of course, doubles the warning distance for steering.

There are other variations that are easily accommodated as well. Instead of a step change in lateral acceleration, a sinusoidal variation in lateral acceleration can be used. This also leads to a simple adjustment of the threshold that also involves applying a fixed multiplier to the threshold. Since the threshold is likely to be tuned in the vehicle during engineering development, these adjustments are not necessary to pursue analytically.

The remainder of this document, however, uses the approach that allows only for the single step change in lateral acceleration before the hazard is reached.

Computing lateral acceleration values

Assume the vehicle is in steady-state cornering, with vehicle coordinate system origin O moving with velocity vector $\underline{\boldsymbol{V}}$. The yaw rate *r*, path radius *R*, forward speed *u*, speed tangential to the arc *V*, the lateral acceleration a_y are related as follows:

$$r = \frac{V}{R}, \quad a_y = V\,r = \frac{V^2}{R}, \quad u = V\cos\beta \ .$$

Consider now a point P which represents a point hazard, as shown in Figure 6. (The results will be generalized later to handle finite-sized hazard regions that must be avoided. In addition, even a continuous road edge can be represented by a series of points at the road edge.)

Let *d* be the distance from origin O to P, and let ϕ be the angle between the current velocity vector $\underline{\boldsymbol{V}}$ and the vector from O to P. If the sideslip angle β is known or estimated and the sensor system has estimates of the distance to the hazard and its location with respect to the vehicle coordinate, then *d* and ϕ are known.

Note also that

$$\phi_P = \beta + \theta_P \ ,$$

where θ_P is the azimuth angle from the vehicle longitudinal *x* axis to the hazard.

As shown in the figure, assume that the current yaw rate *r* and speed *V* means that the origin of the vehicle coordinate system will not intersect with P. Instead, define a new path radius R_P that would lead to such an intersection. The center of curvature for this new path will be normal to the line segment OP and the new radius can be easily derived as

$$R_P = \frac{d}{2\sin\phi} \ .$$

The associated yaw rate r_P and lateral acceleration $a_{y,P}$ to follow this path are:

$$r_P = \frac{V}{R_P}, \quad a_{y,P} = V \cdot r_P = \frac{2V\sin\phi_P}{d} \ .$$

Recall the warning rule equation (3):

$$(a_{y,R} - \Delta a_y{*}) \le a_y \le (a_{y,L} + \Delta a_y{*})$$

This now becomes:

Warn when any of the following equivalent conditions are met

$$
\begin{array}{ccccc}
(V\,r_R - \Delta a_y *) & \le & V\,r & \le & (V\,r_L + \Delta a_y *) \\
(r_R - \dfrac{\Delta a_y *}{V} & \le & r & \le & (rL + \dfrac{\Delta a_y *}{V}) \\
(\dfrac{2V \sin \phi_R}{d_R} - \dfrac{\Delta a_y *}{V}) & \le & r & \le & (\dfrac{2V \sin \phi_L}{d_L} + \dfrac{\Delta a_y *}{V}) \\
(\dfrac{\sin \phi_R}{d_R} - \dfrac{\Delta a_y *}{2V^2}) & \le & \dfrac{r}{2V} & \le & (\dfrac{\sin \phi_L}{d_L} + \dfrac{\Delta a_y *}{2V^2})
\end{array} \tag{4}
$$

Yet another equivalent expression set is derived simply by rearranging the final expression given above, and solving each of the two inequalities for the distance to the left- and right-side points associated with a hazard:

Warn if two conditions hold:

$$
\frac{d_R}{\sin \phi_R} \ge \frac{2V}{r + \dfrac{\Delta a_y *}{r}} \quad \textit{and} \quad \frac{d_L}{\sin \phi_L} \le \frac{2V}{r - \dfrac{\Delta a_y *}{r}}
$$

A first suggestion is that $\Delta a_y * = 2$ m/s^2.

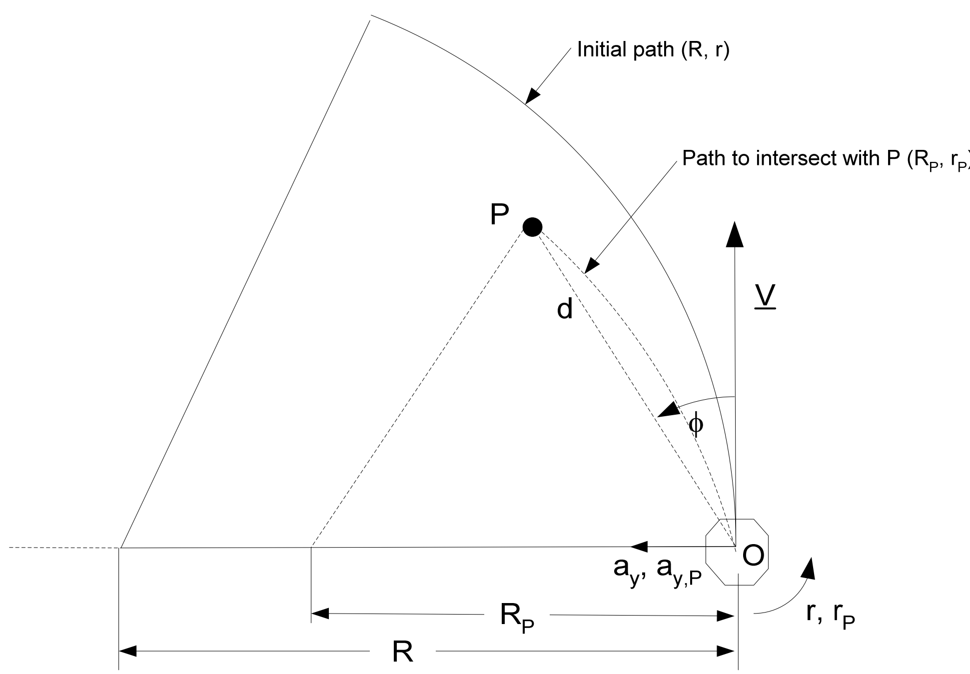


Figure 6 Steady-state cornering paths associated with avoiding hazard P

Accounting for vehicle width

Assume the vehicle width is *w*, as measured between the outer edges of the tires on the widest axle. Then the relationships above hold if we adjust ϕ to a value ϕ_w to move the hazard point P_L to the left by *w/2* and P_R to the right by *w/2* :

$\phi_w = \phi + \frac{w}{2d}$ for the left side of a hazard, and

$\phi_w = \phi - \frac{w}{2d}$ for the right side of a hazard.

Accounting for towed trailers

Towed trailers are not addressed in this document. Additional maneuvering room would need to be allowed for towed trailers. "Off-tracking" is the tendency of trailers to cut corners, and the values depend on the configuration of the axles, the towing mechanisms, speed, and the loading of the tractor and trailer.

Conclusion

The Task 2 report presented a recommended set of algorithms and driver interface concepts that could serve as the basis for a prototype vehicle system. When integrated with the remote sensing system to detect relevant hazards, the result should be a reasonable first implementation of a technology that may be capable of preventing the set of rollover crashes during military operations that are due to unseen negative terrain features. The interface concepts include an auditory alert coupled at specific times with a visual display of a driver's view of the roadway with an overlay of hazard locations. The algorithms assume that a driver's response to the alert would be at least equivalent in evasion effectiveness as applying a specified level of braking or a different specified level of additional lateral acceleration to avoid the hazard. Finally, an appendix is included to advise on the use of GPS alone to estimate vehicle speed and yaw rate. While vehicle speed is possible with GPS, yaw rate will very likely require a separate sensor.

Acknowledgments

Scott Bogard of UMTRI contributed the appendix of this report. Discussions with Tim Gordon of UMTRI were helpful to the development of the threat assessment approach.

References

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[2] Campbell, J.L., Richard, C.M., Brown, J.L., & McCallum, M. (2006). Crash Warning System Interfaces: Human Factors Insights and Lessons Learned, Final Report. Seattle, WA: Battelle Center for Human Performance and Safety.

[3] LeBlanc, D., Sayer, J., Winkler, C., Bogard, S., Devonshire, J. Mefford, M., Hagan, M., Bareket, Z., Goodsell, R., and Gordon, T. "Road departure crash warning system (RDCW) field operational test final report." University of Michigan Transportation Research Institute technical report 2006-9-1 and 2006-9-2, June 2006.

Appendix A: Using GPS for vehicle speed and yaw rate

This appendix reports on comparisons of the GPS-based measurements for vehicle speed and vehicle yaw rate with measurements of those same quantities that used, respectively, ABS wheel speed sensors and a fiber optic yaw rate gyro. The comparisons are not statistical in nature, but are based on a few samples of data from a previous project in which data was collected from a fleet of 11 vehicles equipped with GPS, yaw rate gyros, and ABS wheel speed sensors [3]. Although 83,000 miles of data was collected, only a few trips are presented here. The conclusions seem to be borne out by even this small set of data.

The GPS receiver was a Trimble differential GPS receiver configured for a 5 Hz real time update using a satellite-based differential correction broadcast (OmniSky). The yaw rate sensor was a KVH fiber optic gyro, and the vehicle speed was from the OEM sensors on a 2003 Nissan Altima 3.5SE. Nissan provided UMTRI with the vehicle CAN bus data protocols for the Road Departure Crash Warning System Field Operational Test [3].

A.1 Vehicle speed from GPS

Shown in Figure A.1 is a plot of measured and GPS speed as function of time for a trip that had a distance of 90,956 m and lasted just over an hour. The figure shows an overall agreement between the two signals at least at the level of detail shown in the figure. Also, evident in the figure are clear dropouts in GPS speed, with the most obvious examples occurring around 1560 and 1870 sec.

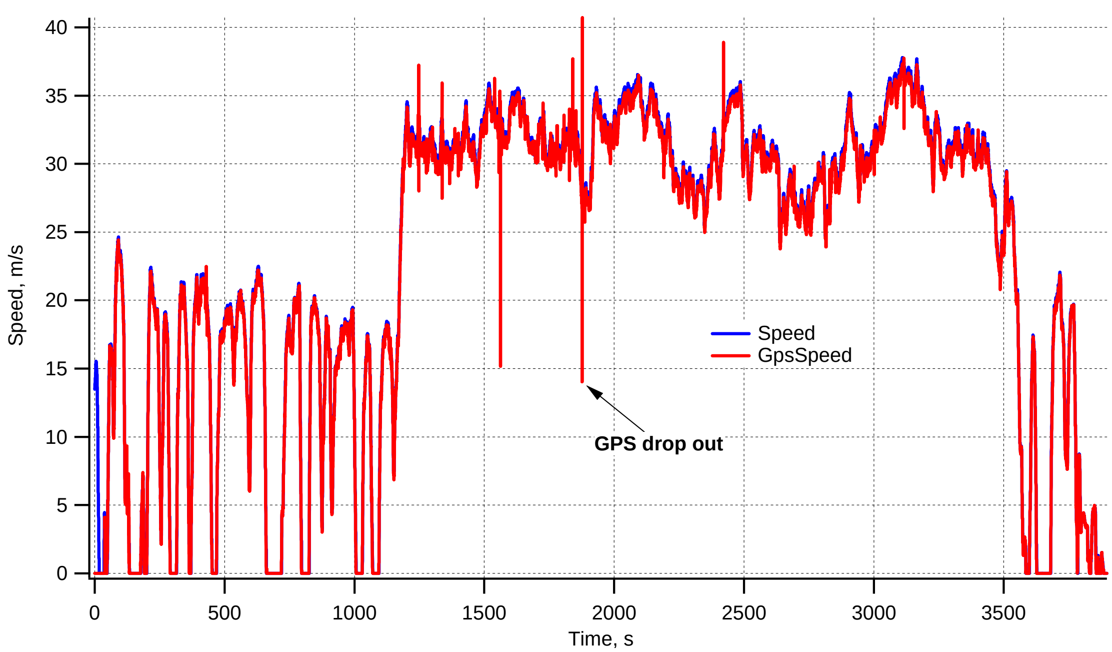

Figure A.1. Speed and GPS Speed as a function of time

A closer look at the signals shows that the GPS errors occur at times when the number of satellites is changing and that the most severe errors occur when the number of satellites drops to three or four. Some examples of these errors are shown in Figure A.2 below which includes the number of satellites as a function of time in addition to speed and GPS speed (labeled as GPSSpeed in the figure).

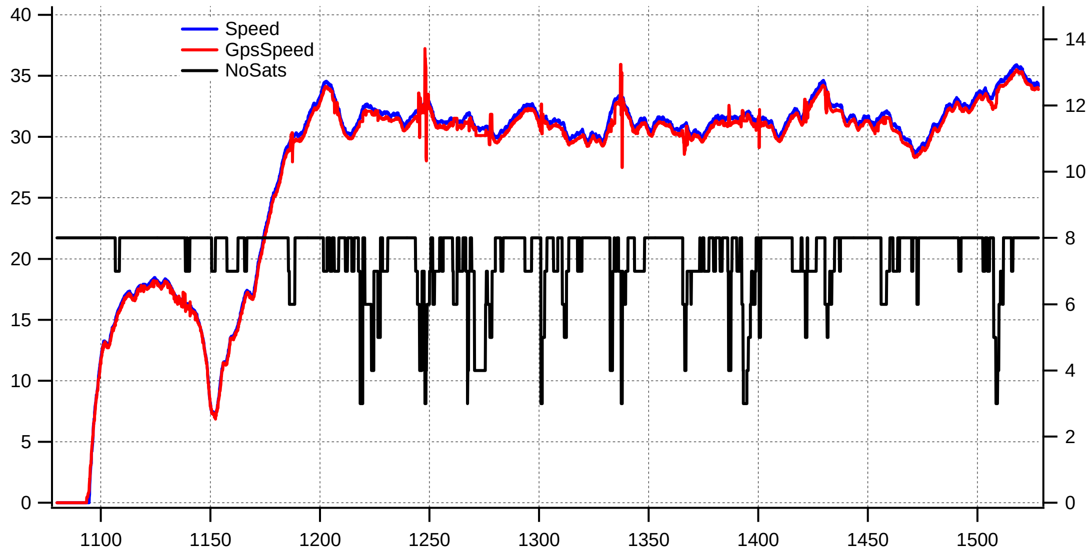

Figure A.2. Speed, GPS speed, and number of satellites as a function of time

To quantify the duration and severity of the GPS errors, consider Figure A.3 which shows an expanded view of a single episode of GPS speed error. In this example, the duration of the error is 0.9 seconds and the maximum error between the signals is approximately 14 percent. A second example of GPS error is shown in Figure A.4 and lasts 1.1 s. In this example, the error between the signals is over 50 percent. Note that these errors are associated with the number of satellites dropping to three or four. Since four is the absolute minimum number required to compute new GPS values, it seems clear that in practice, GPS signals alone cannot be used for updates in vehicle speed unless the number of satellites is at least five.

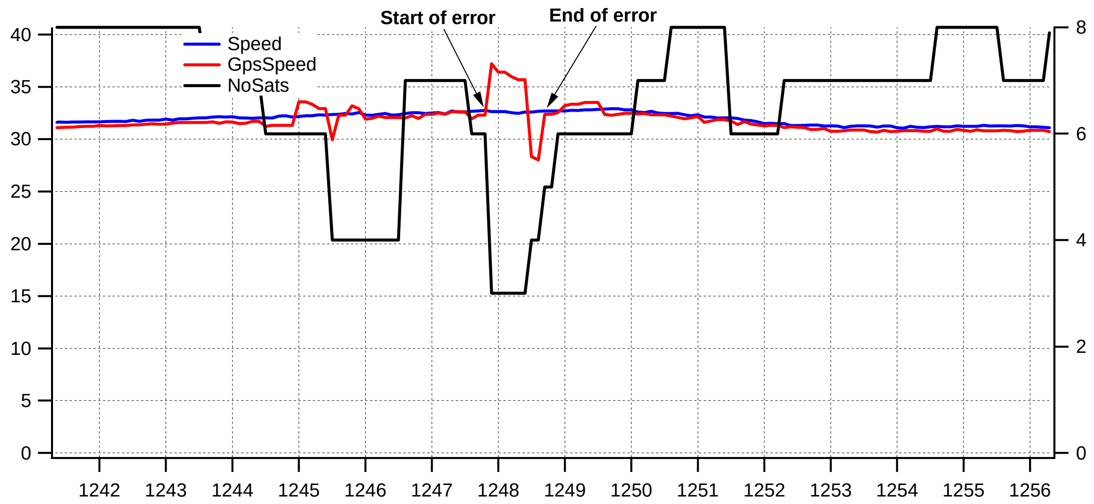

Figure A.3 Example of a 14 percent GPS Speed error with a 0.9 s duration.

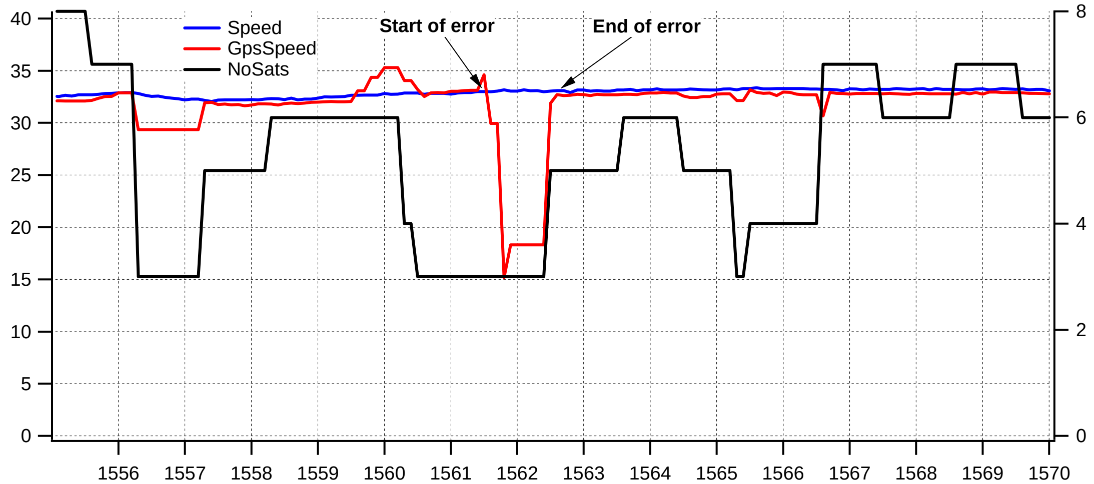

Figure A.4. Example of 50 percent GPS speed error with a 1.1 s duration

Finally, consider Figure A.5 which shows the difference between Speed and GPS speed for the same set of data. Summarizing these data shows that there is on average a 0.34 m/s offset between the two signals and that the RMS between the signals is 0.95 m/s.

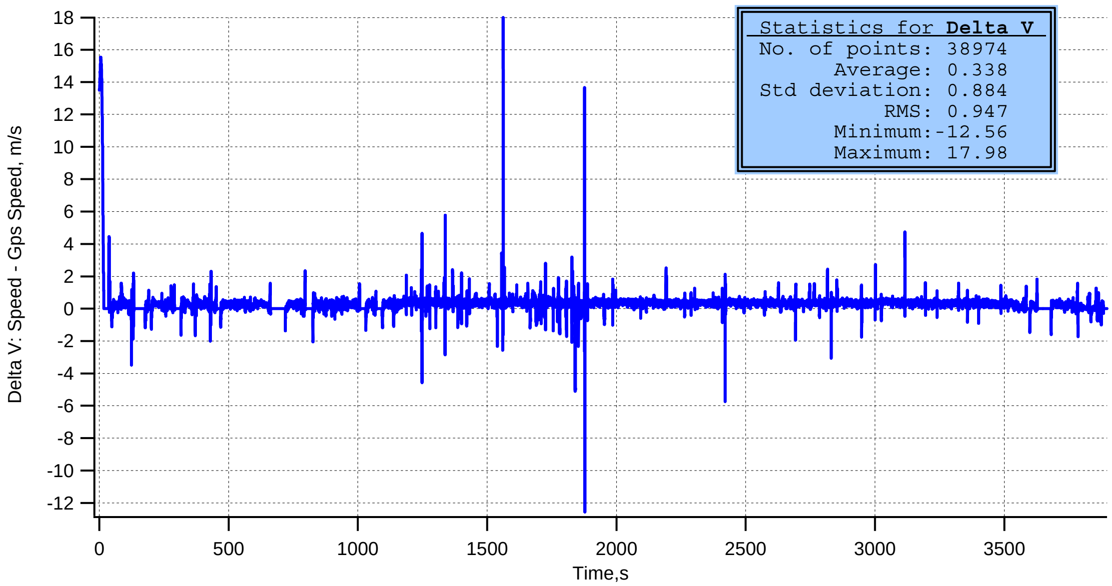

Figure A.5. Statistics for the difference between speed and GPS speed

A.2 Yaw rate from GPS

Figure A.6 shows an example of speed, yaw rate, GPS heading and number of satellites as a function of time for a 26 minute trip from the RDCW database (LeBlanc et. al, 2005). The trip covers a broad range of speeds and includes many turning events as shown by the large spikes in yaw rate and corresponding large changes in heading angle. Also of note is the discontinuity in GPS heading around due North (0 to 360 degrees), which when differentiated to estimate yaw rate must treated as a special case.

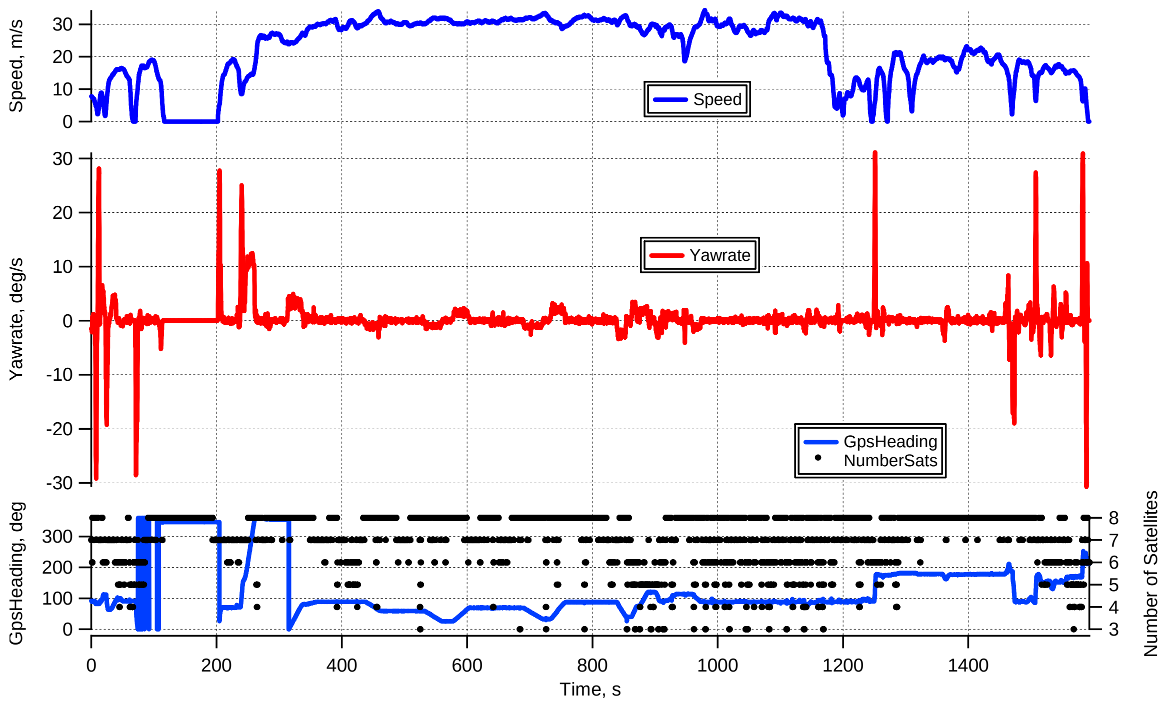

Figure A.6. Example of speed, yaw rate, GPS heading and number of satellites as function of time

Figure A.7 is a 50 sec sample of yaw rate (from a gyro) and GPS estimate of heading for a low speed period during the trip first shown in Figure A.1. For comparison this figure also shows the derived GPS yaw rate ("GPSYawratesm") on the same ordinate axis as the measured yaw rate. GPSYawratesm was calculated by differentiating GPS heading and applying a phase lagged moving average filter over a 0.5 s window prior to the point of interest. This simulates a real-time filtering of the signal. Observations regarding the GPS-based estimate of yaw rate include:

- Noise—even with a half-second moving average filter the signal still has a lot noise relative to the measured yaw rate signal.
- Phase lag—to address noise, the signal must be smoothed which in a real-time system introduces lags that may be unacceptable for some applications and real-time algorithms.

- Slow update rates: In this case the GPS heading signal was not updated during slow maneuvers in a parking lot. These maneuvers are seen in the measured yaw rate signal between 5 and 15 s but are not being captured by the GPS heading signal. Later, in another maneuver (20 to 25 s) the heading change is reflected but there is a delay of 1 or 2 s before it changes which introduces large discontinuities in the GPSYawratesm single. The fact that GPS heading does not update at low speeds may be a function of the particular receiver used; since heading is based on North and East speed components, it is reasonable that a receiver would not provide highly noisy heading results at low speeds where the signal to noise for speed components would be poor.

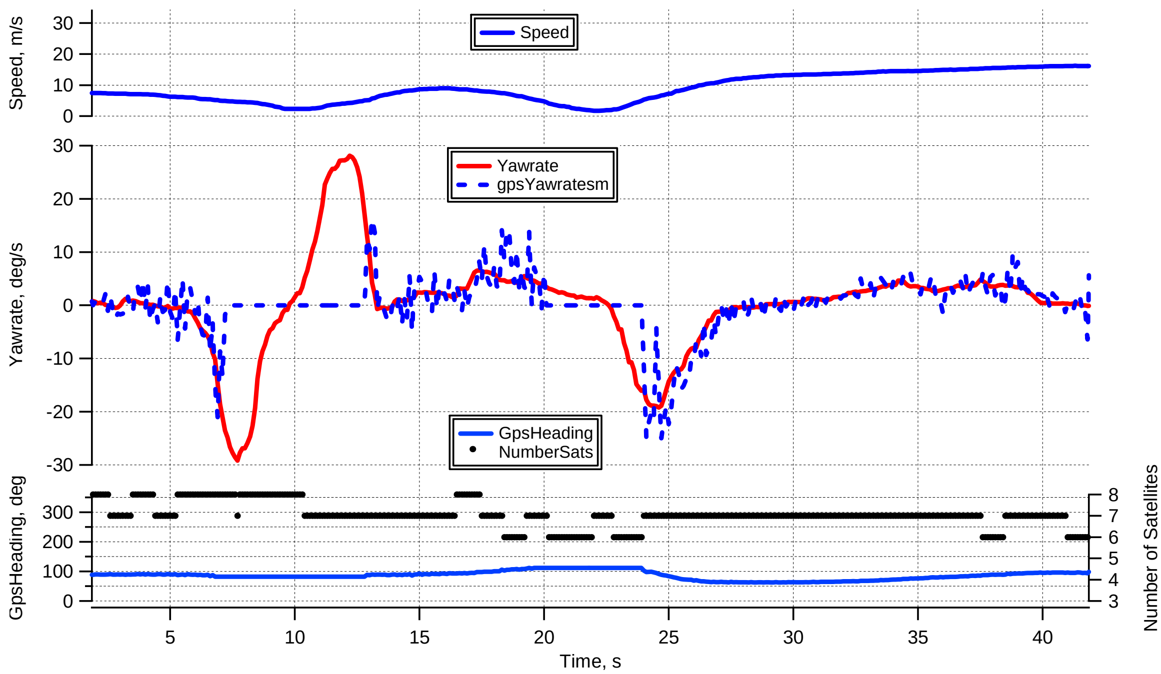

Figure A.7. Example comparing the GPS-derived yaw rate signal (filtered) with the measured yaw rate for a 50 second period of slow speed.

Figure A.8 is another example comparing measured yaw rate to the derived GPSYawratesm signal. In this example, a high-speed trip segment was chosen. This example illustrates how changing satellite coverage can introduce large amounts of noise in the signal. Around 855 s in the figure the number of satellites drops from seven to three which causes a marked change in the estimated GPS heading angle. This sudden heading change then results in a large amount of variation in the calculated GPSYawratesm signal.

Finally, consider Figure A.9 which illustrates how much error there is between the measured yaw rate and the calculated GPSYawratesm signals as function of speed. This graph was derived by calculating the root-mean-square (RMS) of the difference between yaw rate and GPSYawratesm at nine evenly spaced speed bins each with a 4 m/s window. The estimated RMS values for each speed bin was then approximated with an exponential curve (chisq = 0.76) to get a continuous measure of the error as a function of speed. The figure illustrates that the amount of error between the two signals does change with speed and increases by at least five fold when comparing speeds above 50 mph to speeds below 10 mph. Of course, this graph is specific to the data processing used to calculate GPSYawratesm and would change if a more aggressive filter or sophisticated differential were used to derive GPSYawratesm signal.

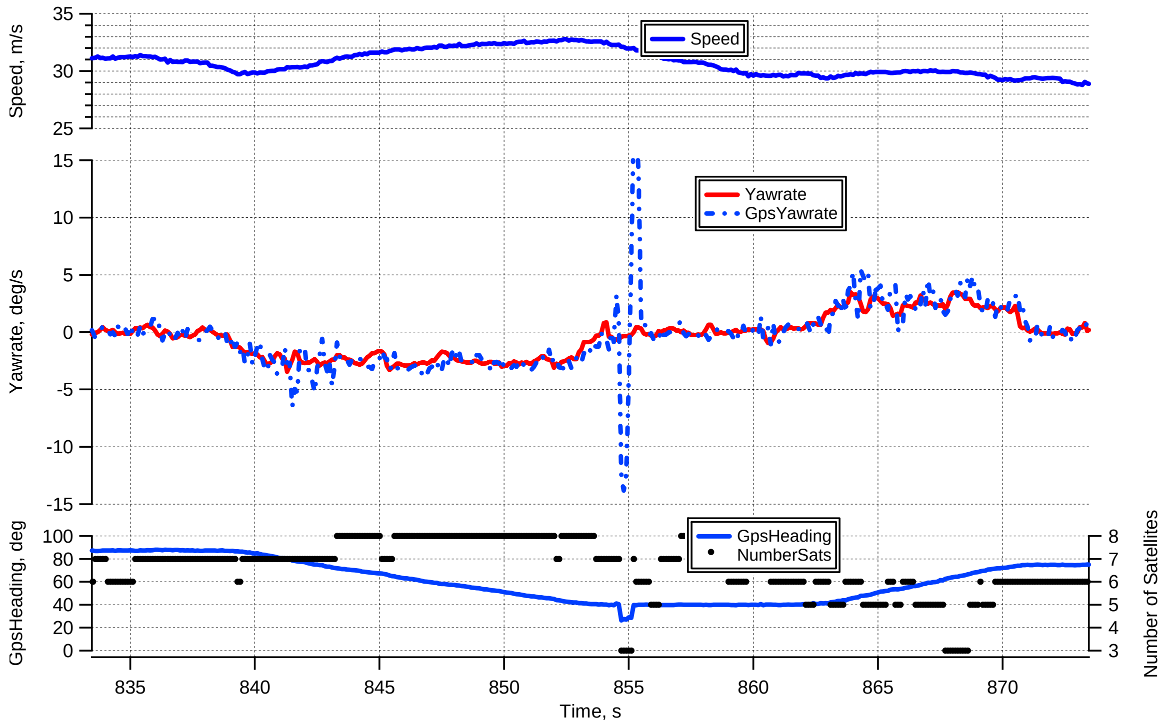

Figure A.8. Example comparing the GPS derived yaw rate signal (filtered) with the measured yaw rate for a 50 second period of high speed.

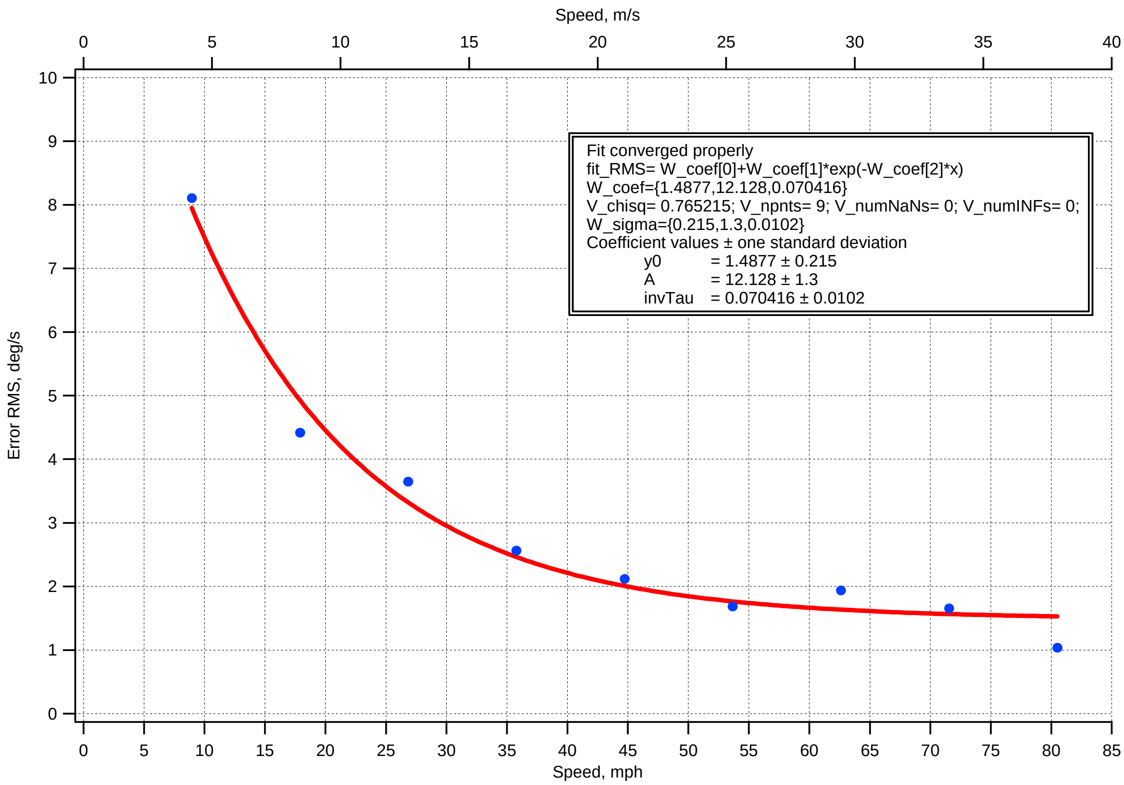

Figure A.9. Estimated RMS error as a function of speed.