(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
3 June 2010 (03.06.2010)

PCT

(10) International Publication Number
WO 2010/062671 A1

(51) International Patent Classification:
B60K 28/16 (2006.01)

(21) International Application Number:
PCT/US2009/062698

(22) International Filing Date:
30 October 2009 (30.10.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/109,584 30 October 2008 (30.10.2008) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

(54) Title: VEHICLE AND METHOD FOR ADVISING DRIVER OF SAME

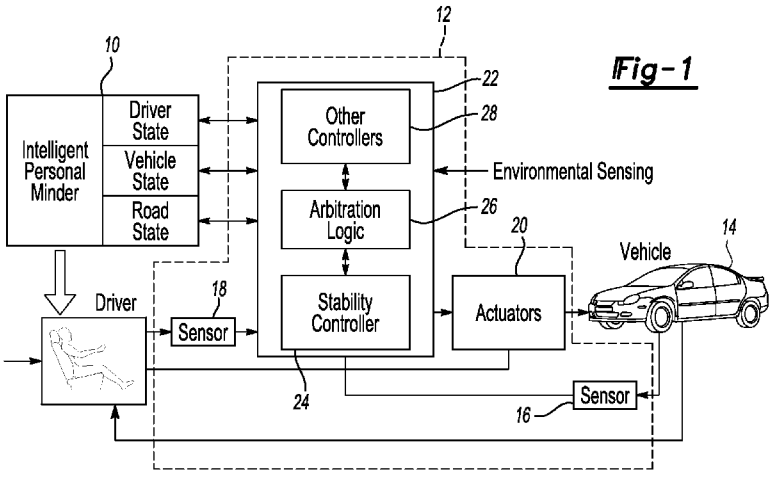


Fig-1

(57) Abstract: A method for advising a driver of a vehicle may include measuring a plurality of parameters representing the vehicle's current handling condition and the vehicle's limit handling condition, determining a margin between the vehicle's current handling condition and limit handling condition, and initiating an alert for the driver before the vehicle achieves the limit handling condition if the margin exceeds a predetermined threshold.

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VEHICLE AND METHOD FOR ADVISING DRIVER OF SAME

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 61/109,584, filed October 30, 2008, which is hereby incorporated by reference in its entirety.

BACKGROUND

Driver error is cited as the cause of 45% to 75% of roadway collisions and as a contributing factor in a majority of all collisions.

Lane-Departure Warning (LDW) uses a vision sensor to detect a vehicle's position relative to a lane and warn the driver of an unintentional lane departure. Certain Forward Collision Warning (FCW) systems use environmental sensors to detect potential safety hazards in front of a vehicle and warn the driver in advance. These existing driver warnings, however, operate during steady-state or quasi-steady-state driving conditions.

SUMMARY

An automotive vehicle may include at least one of an electronic stability control system, anti-lock braking system and traction control system, and at least one computing device. The at least one computing device may be configured to initiate an alert for a driver before the at least one of the electronic stability control system, anti-lock braking system and traction

control system activates based on a margin between the vehicle's current handling condition and limit handling condition.

While example embodiments in accordance with the invention are illustrated and disclosed, such disclosure should not be construed to limit the invention. It is anticipated that various modifications and alternative designs may be made without departing from the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a block diagram of an embodiment of a vehicle control system.

FIGURE 2 is a plot of example vehicle speed, traction and braking profiles.

FIGURES 3A through 3C are plots of example vehicle motion states of yaw rate and sideslip angle.

FIGURES 4A through 4C are plots of example yawing, longitudinal, and sidesliping handling limit margins.

FIGURE 5 is a plot of example vehicle speed, traction and braking profiles.

FIGURES 6A through 6C are plots of example vehicle motion states of yaw rate and sideslip angle.

FIGURES 7A through 7C are plots of example yawing, longitudinal, and sidesliping handling limit margins.

FIGURE 8 is a plot of example membership functions characterizing four driver categories based on handling risk factor.

FIGURES 9A, 10A and 11A are plots of example final handling limit margins and risk.

FIGURES 9B, 10B and 11B are plots of example probabilities of driver style.

FIGURE 12 is a plot of example determinants of smooth and abrupt driving behaviors.

FIGURES 13A and 13B are plots of example mean gap times for aggressive and cautious driving respectively.

FIGURES 14A and 14B are plots of example standard deviations of accelerator pedal rate for aggressive and cautious driving respectively.

FIGURES 15A and 15B are plots of example standard deviations of brake pedal rate for aggressive and cautious driving respectively.

FIGURES 16A and 16B are plots of example driver indices for aggressive and cautious driving respectively.

FIGURE 17 is a plot of an example relative range, range-error and longitudinal acceleration between a leading and following car for aggressive driving.

FIGURE 18 is a plot of select example parameters characterizing the aggressive driving of Figure 17.

FIGURE 19 is a plot of an example relative range, range-error and longitudinal acceleration between a leading and following car for cautious driving.

FIGURE 20 is a plot of select example parameters characterizing the cautious driving of Figure 19.

FIGURES 21 through 23 are block diagrams of embodiments of driver advisory systems.

DETAILED DESCRIPTION

I. Introduction

An objective of existing vehicle electronic control systems is to facilitate the driving task by identifying driver intent and aiding the driver by controlling the vehicle to achieve the driver intent safely, robustly, and smoothly. The control effectiveness of electronic control systems may be significantly increased when the driver and the electronic control system work together towards the same accident avoidance goal and maximize the accident avoidance capability of the driver-in-the-loop vehicle as a system. One approach to achieve this is to provide timely clear and transparent advisory information to a driver such that a responsible driver can respond accordingly. Such advisory information can be gathered or computed from sensors normally found on a vehicle, which implement a bilateral closed-loop control between the driver and the electronic control. The electronic control follows the driver intent and the driver responds to the advisory information from the electronic control to modify his drive inputs (such as dropping throttle, easing steering inputs, *etc*.) In this way, a seamless coordination between the driver and the electronic control system is possible and is likely to minimize the effect of potential safety hazards due to driver errors.

We consider, *inter alia*, warnings that occur close to the handling limit, a driving or maneuvering condition in which vehicle stability controls usually intervene. In addition to problems encountered near the handling limit, the driver advisory system approach

discussed herein can also be used to improve fuel economy, *i.e.*, a system which can use advising and/or coaching to help the driver learn driving habits that conserve fuel. We also discuss using data from vehicle stability controls to provide real-time warnings when the vehicle approaches the handling limit. This may be part of a cluster of warning functions that may be defined as an Intelligent Personal Minder (IPM) system. Generally speaking, the intelligence computed for the IPM system can be sent to warn or advise a driver through various devices including a haptic pedal, a heads-up-display, an audio warning device, a voice system, *etc.*

Figure 1 depicts the interaction of an embodiment of an IPM system 10 with other components/subsystems 12 of a vehicle 14. The other components/subsystems 12 may include vehicle sensors 16, 18 (*e.g.*, a yaw rate sensor, steering angle sensor, lateral acceleration sensor, longitudinal acceleration sensor, wheel speed sensor, brake pressure sensor, *etc.*), actuators 20 and one or more controllers 22. The one or more controllers 22 may include stability control 24, arbitration logic 26 and other controllers/systems 28 (*e.g.*, anti-lock braking system, traction control system, *etc.*)

For any control system, the plant model may play a role in designing an effective control strategy. Similarly, a driver model is important for generating effective and appropriate driver advisory signals. Hence, driving style characterization may be needed. We discuss methods of identifying a driver's characteristics based on his or her vehicle handling capability. While driver modeling and driver behavior characterization have been

studied, we suggest an approach in which the driving behavior/style and/or the driving experience level may be deduced, for example, based on the frequency and duration of driving close to the handling limit (as well as other techniques). Such driver characterization information may be used in a variety of applications, some of which are discussed below.

II. A Brief Discussion Of Vehicle Stability Controls

A vehicle's handling determines the vehicle's ability to corner and maneuver. The vehicle needs to stick to the road with its four tire contact patches in order to maximize its handling capability. A tire which exceeds its limit of adhesion is either spinning, skidding or sliding. A condition where one or more tires exceed their limits of adhesion may be called a limit handling condition and the adhesion limit may be called a handling limit. Once a tire reaches its handling limit, the average driver is usually no longer in control. In the so-called understeer case, the car under performs a driver's steering input, its front tires pass their handling limit, and the vehicle continues going straight regardless of the driver’s steering request. In the so-called oversteer case, the car over performs the driver's steering inputs, its rear tires pass their handling limit, and the vehicle continues spinning. For safety purposes, most vehicles are built to understeer at their handling limits.

In order to compensate vehicle control in case a driver is unable to control the vehicle at or beyond the handling limit, electronic stability control (ESC) systems are designed to redistribute tire forces to

generate a moment that can effectively turn the vehicle consistent with the driver's steering request. Namely, to control the vehicle to avoid understeer and oversteer conditions.

Since its debut in 1995, ESC systems have been implemented in various platforms. Phasing in during model year 2010 and achieving full installation by model year 2012, Federal Motor Vehicle Safety Standard 126 requires ESC systems on any vehicle with a gross weight rating below 10,000 lb. ESC systems may be implemented as an extension of anti-lock braking systems (ABS) and all-speed traction control systems (TCS). They may provide the yaw and lateral stability assist to the vehicle dynamics centered around the driver's intent. It may also proportion brake pressure (above or below the driver applied pressure) to individual wheel(s) so as to generate an active moment to counteract the unexpected yaw and lateral sliding motions of the vehicle. This leads to enhanced steering control at the handling limits for any traction surface during braking, accelerating or coasting. More specifically, current ESC systems compare the driver's intended path to the actual vehicle response which is inferred from onboard sensors. If the vehicle's response is different from the intended path (either understeering or oversteering), the ESC controller applies braking at selected wheel(s) and reduces engine torque if required to keep the vehicle on the intended path and to minimize loss of control of the vehicle.

A limit handling condition can be detected using data already existing in ESC systems, so new sensors may not be required. Consider, for example, a vehicle equipped with an ESC system using a yaw rate

sensor, a steering wheel sensor, a lateral accelerometer, a wheel speed sensors, a master cylinder brake pressure sensor, a longitudinal accelerometer, *etc*. The vehicle motion variables are defined in the coordinate systems as defined in ISO-8855, where a frame fixed on the vehicle body has its vertical axis up, longitudinal axis along the longitudinal direction of the vehicle body, and a lateral axis pointed from the passenger side to the driver side.

Generally speaking, vehicle level feedback controls can be computed from individual motion variables such as yaw rate, sideslip angle, or their combination together with arbitrations among other control commands such as driver braking, engine torque request, ABS and TCS. Vehicle level control commands are discussed in the following.

The well-known bicycle model captures the vehicle dynamics, its yaw rate ω_z along the vertical axis of the vehicle body and its sideslip angle β_r defined at its rear axle, and obeys the following equations

$$\begin{aligned} I_z\dot{\omega}_z &= -b_f c_f\left(\beta_r + b\omega_{zt}v_x^{-1} - \delta\right) + b_r c_r \beta_r + M_z \\ M\left(\dot{v}_x\beta_r + v_x\dot{\beta}_r + b_r\dot{\omega}_z + \omega_z v_x\right) &= -c_f\left(\beta_r + b\omega_z v_x^{-1} - \delta\right) - c_r\beta_r \end{aligned} \qquad (1)$$

where v_x is the vehicle's travel speed, M and I_z are the total mass and the yaw moment of inertia of the vehicle, c_f and c_r are the cornering stiffness of the front and rear tires, b_f and b_r are the distances from the center of gravity of the vehicle to the front and rear axles, $b = b_f + b_r$, M_z is the active moment applied to the vehicle, and δ is the front wheel steering angle.

A target yaw rate ω_{zt} and a target sideslip angle β_{rt} used to reflect the driver's steering intent can be calculated from (1) using the measured steering wheel angle δ and the estimated travel velocity v_x as the inputs. In such a computation, we assume that the vehicle is driven on a road of normal surface condition (*e.g.*, high friction level with nominal cornering stiffness c_f and c_r). Signal conditioning, filtering and nonlinear corrections for steady state limit cornering may also be performed in order to fine tune the target yaw rate and the target sideslip angle. These calculated target values characterize the driver's intended path on a normal road surface.

The yaw rate feedback controller is essentially a feedback controller computed from the yaw error (the difference between the measured yaw rate and the target yaw rate). If the vehicle is turning left and $\omega_z \geq \omega_{zt} + \omega_{zdbos}$ (where ω_{zdbos} is a time varying deadband), or the vehicle is turning right and $\omega_z \leq \omega_{zt} - \omega_{zdbos}$, the vehicle is oversteering and activating the oversteer control function in ESC. For instance, the active torque request (applied to the vehicle for reducing the oversteer tendency) might be computed as in the following

during a left turn: $M_z = \min(0, -k_{os}(\omega_z - \omega_{zt} - \omega_{zdbos}))$

during a right turn: $M_z = \max(0, -k_{os}(\omega_z - \omega_{zt} + \omega_{zdbos}))$ (2)

where k_{os} is a speed dependent gain which might be defined as in the following

$$k_{os} = k_0 + (v_x - v_{xdbl})\frac{k_{dbu} - k_{dbl}}{v_{xdbu} - v_{xdbl}} \quad (3)$$

with parameters $k_0, k_{dbl}, k_{dbu}, v_{xdbl}, v_{xdbu}$ being tunable.

If $\omega_z \leq \omega_z - \omega_{zdbus}$ (where ω_{zdbus} is a time varying deadband) when the vehicle is turning left or $\omega_z \geq \omega_z + \omega_{zdbus}$ when the vehicle is turning right, the understeer control function in ESC is activated. The active torque request can be computed as in the following

$$\begin{aligned} &\text{during a left turn:} \quad M_z = \max(0, -k_{us}(\omega_z - \omega_{zt} + \omega_{zdbus})) \\ &\text{during a right turn:} \quad M_z = \min(0, -k_{us}(\omega_z - \omega_{zt} - \omega_{zdbus})) \end{aligned} \quad (4)$$

where k_{us} is a tunable parameter.

The sideslip angle controller is a supplementary feedback controller to the aforementioned oversteer yaw feedback controller. It compares the sideslip angle estimation β_r to the target sideslip angle β_{rt}. If the difference exceeds a threshold β_{rdb}, the sideslip angle feedback control is activated. For instance, the active torque request is calculated as in the following

during a left turn,

$$\beta_r \geq 0 : M_z = \min(0, k_{ss}(\beta_r - B_{rt} - B_{rdb}) - k_{sscmp}\dot{\beta}_{rcmp}) \quad (5)$$

during a right turn,

$$\beta_r < 0 : M_z = \max(0, k_{ss}(\beta - B_{rt} + B_{rdb}) - k_{sscmp}\dot{\beta}_{rcmp})$$

where k_{ss} and k_{sscmp} are tunable parameters and $\dot{\beta}_{rcmp}$ is a compensated time derivative of the sideslip angle.

Other feedback control terms based on variables such as yaw acceleration and sideslip gradient can be similarly generated. When the dominant vehicle motion variable is either the yaw rate or the sideslip angle, the aforementioned active torque can be directly used to determine the necessary control wheel(s) and the amount of brake pressures to be sent to corresponding control wheel(s). If the vehicle dynamics are dominated by multiple motion variables, control arbitration and prioritization will be conducted. The final arbitrated active torque is then used to determine the final control wheel(s) and the corresponding brake pressure(s). For example, during an oversteer event, the front outside wheel is selected as the control wheel, while during an understeer event, the rear inside wheel is selected as the control wheel. During a large side-slipping case, the front outside wheel is always selected as the control wheel. When both the side slipping and oversteer yawing happen simultaneously, the amount of brake pressure may be computed by integrating both yaw error and the sideslip angle control commands.

Besides the above cases where the handling limit is exceeded due to the driver's steering maneuvers, a vehicle can reach its limit handling condition in its longitudinal motion direction. For example, braking on a snowy and icy road can lead to locked wheels, which increases the stopping distance of the vehicle. Open throttling on a similar road can cause the drive wheels to spin without moving the vehicle forward. For this reason, the handling limit may also be used for these

non-steering driving conditions. That is, the conditions where the tire longitudinal braking or driving forces reach their peak values may also be included in a definition of the handling limit.

The ABS function monitors the rotational motion of the individual wheels in relation to the vehicle's travel velocity, which can be characterized by the longitudinal slip ratios λ_i, with i = 1, 2,3, 4 for the front-left, front-right, rear-left and rear-right wheels, computed as in the following

$$\lambda_1 = \frac{\kappa_1\omega_1}{\max\left(\left(v_x + \omega_z t_f\right)\cos(\delta) + \left(v_y + \omega_z b_f\right)\sin(\delta), v_{\min}\right)} - 1$$

$$\lambda_2 = \frac{\kappa_2\omega_2}{\max\left(\left(v_x + \omega_z t_f\right)\cos(\delta) + \left(v_y + \omega_z b_f\right)\sin(\delta), v_{\min}\right)} - 1 \qquad (6)$$

$$\lambda_3 = \frac{\kappa_3\omega_3}{\max\left(v_x - \omega_z t_r, v_{\min}\right)} - 1,\ \lambda_4 = \frac{\kappa_4\omega_4}{\max\left(v_x + \omega_z t_r, v_{\min}\right)} - 1$$

where t_f and t_r are the half tracks for the front and rear axles, ω_i is the i^{th} wheel speed sensor output, κ_i is the i^{th} wheel speed scaling factor, v_y is the lateral velocity of the vehicle at its c.g. location, and $v_{\min}$ is a preset parameter reflecting the allowable minimum longitudinal speed. Notice that (6) is only valid when the vehicle is not in the reverse driving mode. When the driver initiated braking generates too much slip (*e.g.*, $-\lambda_i \geq \lambda_{bp}$ = 20%) at a wheel, the ABS module will release the brake pressure at that wheel. Similarly, during a large throttle application causing a large slip on the i^{th} driven wheel, the TCS module will request engine torque reduction and/or brake pressure applied to the opposite wheel at the same axle. Consequently, ABS or TCS

activations can be predicted by monitoring how close λ_is are from λ_{bp} and λ_{tp}.

III. Handling Limit Minder

While the aforementioned ESC (including ABS and TCS) is effective in achieving its safety goal, further enhancement is still possible. For example, augmentation of ESC systems may be desirable for roll stability control. The appropriate correction which ESC tries to make, however, may be counteracted by the driver or ambient conditions. A speeding vehicle, whose tire forces go far beyond the traction capability of the road and the tires, might not be able to avoid an understeer accident even with ESC intervention.

We introduce an integration of the driver and ESC system such that they may work cooperatively towards an enhanced control performance of the driver-in-the-loop system. In certain embodiments, the proposed Handling Limit Minder (HLM) determines how close the current driving condition is to the handling limit.

Generally speaking, accurate determination of the handling limit conditions would involve direct measurements of road and tire characteristics or very intensive information from many related variables if direct measurements are not available. Currently, both of these methods are not mature enough for real-time implementation.

Due to their feedback feature, ESC systems may be configured to determine the potential limit handling conditions through monitoring the motion variables of a vehicle such as those described in the last section. When the motion variables deviate from their reference values

by a certain amount (*e.g.*, beyond certain deadbands), the ESC systems may start to compute differential braking control command(s) and determine control wheel(s). The corresponding brake pressure(s) is then sent to the control wheel(s) to stabilize the vehicle. The starting point of the ESC activation can be thought of as the beginning of the handling limit.

More specifically, we may define a relative handling limit margin h_x as in the following

$$h_x = \begin{cases} \dfrac{\bar{x} - x}{\bar{x}} \, if \, 0 \le x \le \bar{x} \\ \dfrac{x - \underline{x}}{\underline{x}} \, if \, \underline{x} \le x < 0 \\ 0 \qquad otherwise \end{cases} \tag{8}$$

where x is the deviation of a motion variable from its reference value and $[\underline{x}, \bar{x}]$ defines the deadband interval within which x falls without initiating the ESC, ABS or TCS. x can be any of the control variables defined in the last section (or any other suitable control variable).

The benefit of h_x defined in (8) is that the driving condition can be quantitatively characterized into different categories. For instance, when $h_x \le 10\%$, the driving condition may be categorized as a red zone condition where the driver needs to have special attention or take some special actions (*e.g.*, slowing down the vehicle); when $10\% < h_x < 40\%$, the driving condition may be categorized as a yellow zone condition which needs some level of special attention from the driver; when $40\% < h_x \le 100\%$, the driving condition may be characterized as a normal condition. In the normal

condition, the driver need only to maintain his normal driving attention. Of course, other ranges may also be used.

Various audible and/or visual warnings may be activated to alert a driver about the handling limit margin. When $h_x \leq 10\%$ for example, a warning light/haptic device may activate to inform the driver that they need to slow down. Alternatively, a voice enabled display system may instruct the driver to take particular action. When $10\% < h_x < 40\%$, an audible tone or display may inform the driver that they are approaching unstable driving conditions, *etc*.

More specifically, let us use the control variables computed in the last section to discuss the computation of h_xs. The vehicle's yaw handling limit margin during oversteer situations h_{OS} (where $\omega_z > \omega_{zt}$ when the vehicle is turning to the left and $\omega_z > \omega_{zt}$ when the vehicle is turning to the right) can be computed from (8) by setting $x = \omega_z - \omega_{zt}$ and $\bar{x} = \omega_{zdbos} = -\underline{x}$, where ω_{zdbos} is the oversteer yaw rate deadband as defined in (2).

Similarly, the vehicle's yaw handling limit h_{US} for understeer situations can be computed from (8) by setting $x = \omega_z - \omega_{zt}$ and $\bar{x} = \omega_{zdbus} = -\underline{x}$, where ω_{zdbus} is the understeer yaw rate deadband as defined in (4). Notice that the aforementioned deadbands might be functions of the vehicle speed, the magnitude of the target yaw rate, the magnitude of the measured yaw rate, *etc*. The deadbands for the understeer situation ($x < 0$) and the oversteer situation ($x > 0$) are different and they are tunable parameters.

The vehicle's sideslip handling limit margin h_{SSRA} can be computed from (8) by setting $x = \beta_r - \beta_{rt}$ and $\bar{x} = \beta_{rdb} = -\underline{x}$.

The longitudinal handling limits of the vehicle involve the conditions when either the driving or braking force of the tires approach the handling limit. The traction control handling limit margin for the i^{th} driven wheel h_{TCS_i} can be computed from (8) by setting $x = \lambda_i$, $\underline{x} = 0$, and $\bar{x} = \lambda_{tb}$. The ABS handling limit margin for the i^{th} wheel h_{ABS_i} can also be computed from (8) by setting $x = \lambda_i$, $\underline{x} = \lambda_{bp}$, and $\bar{x} = 0$. The final traction and braking handling limit margins may be defined as

$$h_{ABS} = \min_{i\in\{1,2,3,4\}} h_{ABS_i}, h_{TCS} = \min_{i\in\{1,2,3,4\}} h_{TCS_i} \quad (9)$$

Notice that further screening conditions may be used in computing the aforementioned handling limit margins. For instance, one of the following or the combination of some of the following conditions might be used to set the handling limit margin as 0: a magnitude of the target yaw rate is beyond a certain threshold; a magnitude of the measured yaw rate is greater than a certain threshold; a driver's steering input exceeds a certain threshold; or, extreme conditions such as the vehicle's cornering acceleration is greater than 0.5g, the vehicle's deceleration is greater than 0.7g, the vehicle is driven at a speed beyond a threshold (*e.g.*, 100 mph), *etc.*

In order to test the aforementioned handling limit margin computations and verify their effectiveness with respect to known driving conditions, a vehicle

equipped with a research ESC system developed at Ford Motor Company was used to conduct vehicle testing.

For the driving condition profiled by the vehicle speed, throttling, and braking depicted in Figure 2, the measured and computed vehicle motion variables are shown in Figures 3A through 3C. The corresponding individual handling limit margins h_{US}, h_{OS}, h_{TCS}, h_{ABS}, and h_{SSRA} are shown in Figures 4A through 4c. This test was conducted as a free form slalom on a snow pad with all ESC computations running. The brake pressure apply was turned off in order for the vehicle to approach the true limit handling condition.

For another test, the vehicle was driven on a road surface with high friction level. The vehicle speed, traction and braking profiles for this test are depicted in Figure 5. The vehicle motion states are shown in Figures 6A through 6C. The corresponding individual handling limit margins h_{US}, h_{OS}, h_{TCS}, h_{ABS}, and h_{SSRA} are shown in Figures 7A and 7B.

An envelope variable of all the individual handling limit margins is defined as

$$h_{env} = \min\{h_{OS}, h_{US}, h_{TCS}, h_{ABS}, h_{SSRA}\} \tag{10}$$

Considering that sudden changes in the envelope handling limit margin might be due to signal noises, a low-pass filter $F(z)$ is used to smooth h_{env} so as to obtain the final handling limit margin

$$h = F(z)h_{env} \tag{11}$$

For the vehicle test data shown on Figure 2 and Figures 3A through 3C, the final handling limit margin is depicted in Figure 9A, while for the vehicle test data shown on Figure 5 and Figures 6A through 6C, the final handling limit margin is depicted in Figure 10A.

IV. Handling Limit Driving Style Characterization

In this section, we use the final handling limit margin computed in (11) to characterize vehicle handling related driving conditions and driving style. We introduce the concept of a Handling Risk Factor (HRF) as the measure of how a driving condition is related to the handling limit. The handling risk factor r is defined as the complement of the final handling limit margin h, *i.e.*,

$$r = 1 - h \tag{12}$$

The handling risk factor is minimal (r = 0) when the final handling limit margin h is maximal (h = 1) and vice versa. The HRF may be further used to develop a probabilistic model describing different categories of driving styles which are reflected by the current driving conditions with respect to the handling limit.

Generally speaking, a cautious driver usually drives without frequent aggressiveness, *i.e.*, fast changes of steering, speed and acceleration. Hence, it is reasonable to characterize a cautious driver as one who constantly avoids using extreme driving inputs and getting close to the maximal handling risk. An average driver likely exhibits a higher level of HRF than a cautious driver. An expert driver might be more skilful

in controlling the vehicle, *i.e.*, he can drive with a relatively high level of HRF for a long duration without having the vehicle pass the maximal handling limit. A reckless driver exhibits a careless handling behavior which is unpredictable and could induce fast changes. The reckless driver is expected to drive with a handling risk factor that might approach the maximum (r = 1) very briefly from time to time, thus causing frequent triggering of the related safety systems (*e.g.*, ABS, TCS, ESC).

Notice that the difference between the expert driver and the reckless driver is that the former can hold a driving condition at a relatively high HRF level for long duration, while the latter can only hold at the similar level for a short duration before causing the vehicle to pass the maximal handling limit due to the driver's poor control capability. Since the handling risk factor ranges defining, for example, cautious, average, expert and reckless driving behavior (with respect to the limit handling conditions) may not be well defined, we use fuzzy subsets to quantify the four categories of drivers. We further evaluate those categories probabilistically based on a specific driver style. The fuzzy subsets associated with the categories of cautious, average, expert and reckless drivers may be described by the following membership functions

$$\mu_c(r), \mu_e(r), \mu_a(r), \mu_r(r)$$

defined over the HRF universe [0, 1]. Figure 8 shows the relationship between the degrees of membership for each of those categories and the HRF.

The membership functions in Figure 8 can be assigned to any event that is represented by a specific HRF with value r_k using a four dimensional vector

$$D_k = [\mu_C(r_k)\ \mu_e(r_k)\ \mu_a(r_k)\ \mu_r(r_k)]^T$$

of its degree of membership to each of the four example categories: cautious, average, expert and reckless. For example, a HRF value r_k = 0.4 (corresponding to handling limit margin value h_k = 0.6) will translate to the degrees of membership to the cautious, average, expert and reckless categories

$$\mu_c(0.4) = 0.46, \mu_e(0.4) = 0.85$$
$$\mu_a(0.4) = 0.09, \mu_r(0.4) = 0.22$$

The membership grades encode the possibilities that the event characterized by a HRF with value r = 0.4 (or the handling limit margin h = 0.6) might be associated with any of the four example partitions. The vector of membership values d_k makes the association between a single driving event and the possible driver characterization with respect to the HRF of that event. In order to characterize the long term behavior of the driver, we need a probabilistic interpretation of the possibilities that are generated by multiple events. By adding the membership values for each event, we essentially aggregate the overall possibilities that a specific driver can be categorized as cautious, average, expert and reckless, *i.e.*, the vector

$$d^* = \sum_{k=1}^{N} [\mu_c(r_k)\mu_e(r_k)\mu_r(r_k)]^T \quad (13)$$

where N is the number of samples. The aggregated possibilities can be considered as frequencies (sometimes referred to as fuzzy frequencies) since they reveal how frequently and to what degree the HRFs for the multiple events can be cascaded to the four example categories. The alternative to aggregating the possibilities, *i.e.*, adding the membership functions, is to add 1 if the specific membership grade $\mu_i(r_k), i \in \{c,a,e,r\}$ is greater than a prescribed threshold value, *e.g.*, 0.8, or 0 otherwise, resulting in calculating the conventional frequency of the four example categories. From the aggregated possibilities, we can calculate the probabilities of the cautious, average, expert and reckless driver style

$$p_i = d_i^* \left(\sum_{j \in \{c,a,e,r\}} d_j^* \right)^{-1} \quad (14)$$

where $i \in \{c,a,e,r\}$. The probabilities are calculated from the aggregated possibilities (fuzzy frequencies) and can be considered fuzzy probabilities. The reason for the fuzziness here is the lack of certainty in characterizing the relationship between the four example categories and the HRF. For the special case of crisply defined categories (represented by intervals rather than fuzzy subsets), the possibilities transform to Boolean values, their aggregated values become frequencies, and consequently the fuzzy probabilities are translated to conventional probabilities.

The most likely driver category i* is the one that is characterized with the highest probability, *i.e.*,

$$i^* = \underset{i\in\{c,a,e,r\}}{\arg\max}(p_i) \tag{15}$$

The frequencies based calculation of the probabilities can be expressed in terms of the average frequencies

$$p_i = d_i^* / N\left(\sum_{j\in\{c,a,e,r\}} d_j^* / N\right)^{-1} \tag{16}$$

Alternatively, it can be expressed through the exponentially weighted average frequencies where the higher weights are assigned to the possibilities that are associated with the most recent events. Numerically, the process of generating a weighted average with higher weights corresponding to the recent observation can be accomplished by applying a low pass filter implementing the exponential smoothing algorithm in the time domain

$$d_{new}^* = (1-\alpha)d_{old}^* + \alpha d_k = d_{old}^* + \alpha(d_k - d_{old}^*) \tag{17}$$

where the constant forgetting factor $0 < \alpha \leq 1$ controls the rate of updating the mean d^* by assigning a set of exponentially decreasing weights to the older observations. For a constant forgetting factor α, expression (17) recursively generates a vector of positive weights

$$W = \left[(1-\alpha)^k \alpha(1-\alpha)^{k-1}\alpha(1-\alpha)^{k-2}\ldots\alpha\right] \tag{18}$$

with a unit sum. Vector W delineates a weighted average type aggregating operator with exponentially decreasing weights that are parameterized by the forgetting factor α. Parameter α defines the memory depth (the length of the moving window) of the weighted averaging aggregating operator. Therefore, the filtered value d^* of the membership grade vector in (17) represents the weighted averages of the individual possibilities over the weights W. Since all of the aggregated possibilities are calculated over the same moving window of length $K_\alpha = 1/\alpha$, we can consider them as representations of the frequencies of the associations with each of the four concepts. Weighted average (17) is calculated over the events with indexes belonging to a soft interval

$$s \in \{k - K_\alpha + 1, k] \tag{19}$$

where symbol { indicates a soft lower bound that includes values with lower indexes than $(k - K_\alpha)$ with relatively low contribution. Consequently, the aggregated possibilities that form the vector d^* can be converted to probabilities according to expression (14).

In certain embodiments, α may be selectable so that a characterization for a desired period of time is achieved. For example, a user may supply input related to α such that every half hour, a characterization is made. Other scenarios are also possible.

For the vehicle testing depicted by Figures 2, 3A through 3C and 4A through 4C, the individual p_i's are shown on Figure 9B indicating that for most of the driving, the driver exhibited a reckless driving

behavior, which is consistent with the large value of the sideslip angle in Figure 3C (peak magnitude of the sideslip angle exceeds 10 degrees). For vehicle testing depicted by Figures 5 through 7C, the individual p_i's are shown in Figure 10B, indicating that the driver initially exhibited an average driver behavior and then transitioned to a reckless driver behavior.

The calculated probabilities define the most likely HRF based characterization of a driver for the time window that is specified by the forgetting factor α. By modifying the moving window, we can learn and summarize the long and short term characterization for a specific driver based on the HRF.

In order to predict the impact of the changes in HRF on the driver's characterization, we introduce the notion of transitional probabilities. The Markov model P probabilistically describes the set of transitions between the current and the predicted value of the driver category:

$$\begin{array}{cc} & p_j(k+1)\rightarrow \\ & \begin{matrix} p_{11} & p_{12} & p_{13} & p_{14} \end{matrix} \\ p_i(k) & \begin{matrix} p_{21} & p_{22} & p_{23} & p_{24} \end{matrix} \\ & \begin{matrix} p_{31} & p_{32} & p_{33} & p_{34} \end{matrix} \\ & \begin{matrix} p_{41} & p_{42} & p_{43} & p_{44} \end{matrix} \end{array}$$

where p_{ij} is the probability of switching from category i at time k to category j at time k+1, and $p_{ii} = \max(p_i)$ is the probability that is associated with the dominating category i at time k, $i, j \in \{c, a, e, r\}$. The transitional probabilities p_{ij} are derived from the transitional

aggregated possibilities that are updated only if i = arg max(p_l) at time k and j = arg max(p_l), $l \in \{c,a,e,r\}$.

$$d^*_{if,new} = \begin{Bmatrix} (1-\alpha)d^*_{if,old} + \alpha d_{i,k} \; if \; j = \underset{l\in\{c,a,e,r\}}{\arg\max}(p_l) \\ (1-\alpha)d^*_{if,old} \qquad otherwise \end{Bmatrix} \tag{20}$$

The transitional probabilities are then calculated by converting the aggregated transitional possibilities to the probabilities. The maximal transitional probability p_{ij} determines the transition from category i to category j as the most likely transition.

Figures 11A and 11B use a driving vehicle test to verify long term driving behavior characterization. The driver generally shows a cautious driving style (which could be a novice, average or expert driver). At around 190 seconds, the vehicle was turned with some degree of aggressiveness which can be seen from the peak at the HRF plot, and the driving style transitioned to the average category. Since no major HRF events were further identified, this category was carried out for the rest of the driving cycle in conjunction with the concept of the long term characterization.

As mentioned above, various audible and/or visual warnings may be activated to alert a driver about the handling limit margin. The margin thresholds that define whether (and/or what type) of warning is to be issued may be altered (or suspended) based on the driver characterization. For example, if it is determined that the driver is an expert driver, the warning threshold may be reduced from $h_x \leq 10\%$ to $h_x \leq 2\%$, or the warnings

regarding the handling limit margin may be suspended (an expert driver may not need the warnings).

V. Unsupervised Driving Style Characterization

During a normal driving maneuver, a driver's long term longitudinal vehicle control may be used to determine driving behavior regardless of the vehicle's dynamic response. For instance, a driver may exhibit a specific longitudinal control pattern during driving on a highway for a long period of time. His pattern of acceleration pedal activation can be smooth or abrupt even in the absence of emergency conditions. The variability of the pedal and its rate change can be used to differentiate between smooth and abrupt application. Such a smooth or abrupt application exhibits strong correlation with fuel economy and acceleration performance when driving conditions are unconstrained. Identifying such driving behaviors can be used, for example, to implement a fuel economy advisor.

Anomaly detection can be used to estimate major changes in the overall variability of the control actions indicating changes in corresponding behaviors. Anomaly detection is a technique that puts a major emphasis on the continuous monitoring, machine learning, and unsupervised classification to identify a trend of departure from a normal behavior and predict potential significant change. The determinant of the covariance matrix of the population of a driver's actions may be used as a measure of the generalized variance (spread) of the population, and hence as an indicator for a change in the driver's behavior.

The feature space of driving torque request τ_d and its derivative is spanned by the vector $y=[\tau_d \dot{\tau}_d]$. The determinant D of the covariance matrix of the population can be recursively calculated as

$$D_{k+1}=(1-\alpha)^{k-1}D_k\left(1-\alpha+(y_k-v_k)Q_k(y_k-v_k)^T\right) \quad (21)$$

with

$$\begin{aligned} v_{k+1} &= (1-\alpha)v_k+\alpha y_k \\ Q_{k+1} &= (I-G_k(y_k-v_k))Q_k(1-\alpha)^{-1} \\ G_{k+1} &= Q_k(y_k-v_k)^T\alpha\left(1-\alpha+\alpha(y_k-v_k)Q_k(y_k-v_k)^T\right)^{-1} \end{aligned} \quad (22)$$

where v_k is a filtered version of y_k, Q_k is the estimated inverse covariance matrix, and α is a constant which reflects the forgetting factor related to the filter memory depth.

D_k thus computed in (21) has initial means and standard deviations for abrupt and smooth type behaviors. The instantaneous behavior is classified as abrupt if its value is higher than a control limit l_{abrupt} and is classified as smooth if its value is lower than a control limit u_{smooth}. l_{abrupt} and u_{smooth} are defined as $l_{abrupt}=\mu_{abrupt}-3\sigma_{abrupt}, u_{smooth}=\mu_{smooth}+3\sigma_{smooth}$ where μ_{abrupt} and σ_{abrupt} are the mean and standard deviation of the abrupt behavior class. μ_{smooth} and σ_{smooth} are similarly defined for the smooth behavior class. If the current behavior is classified as either abrupt or smooth, the corresponding mean and standard deviation of the matching behavior are recursively updated

$$w_{k+1} = (1-\beta)w_k + \beta D_{k+1}$$
$$H_{k+1} = (1-\beta)H_k + (\beta - \beta^2)(D_{k+1} - w_k)^T (D_{k+1} - w_k) \quad (23)$$
$$\sigma_{k+1} = (H_{k+1})^{1/2}$$

where w and H are the estimated mean and variance, and β is another forgetting factor.

Figure 12 shows the determinant of the covariance matrix from the vector of acceleration pedal position and its rate change for 8 runs of vehicle tests. The 4 runs with solid lines of determinant were for abrupt acceleration pedal applications. These determinants show a large value, for example, greater than 7. The 4 runs with dotted lines of determinant were for smooth acceleration pedal applications. These determinants show a small value, for example, less than 4. Hence, the size of the determinant reveals the unique informative patterns which can be used to distinguish smooth driving behavior from abrupt driving behavior.

Since interactions between the driver and the driving environment include frequent vehicle stops with varied durations, suspension of the continual updating may be required to prevent numerical problems during recursive computation. The following suspension conditions may be used: (i) If vehicle speed is less than 1 mph, vehicle speed and acceleration related recursive calculations are suspended. (ii) If the accelerator pedal position is less than 1%, pedal related recursive calculations are suspended.

Although the above deviation focuses on the acceleration pedal, it can be easily applied to the braking case. Since sudden aggressive braking can happen

during emergency situations (which are not necessarily indicative of the driver's general behavior), quasi-steady state driving where braking is not at its extreme may be used for computational screening.

During transient acceleration and deceleration, certain wheels of the vehicle may experience large longitudinal slip, and the tire longitudinal forces of those wheels may reach their peak values. Such conditions can be identified through monitoring the rotational motion of the individual wheels in relation to the vehicle's travel velocity, and consequently the driver behavior during transient maneuvers can be determined as discussed above.

VI. Semi-Supervised Driving Style Characterization

All driver inputs may not be accessible by electronic control systems. Certain variables, however, may construct an input-output pair that may be used to deduce driver control structure. For example, during a car-following maneuver, the relative distance between the leading and following car and the driver's braking and throttle requests are usually well coordinated. Here we consider using a Tagaki-Sugeno (TS) model to relate the variance of the driver's braking and throttling commands to the relative range and velocity between the leading and following car.

A fuzzy system may utilize the signal conditioned mean driving headway (gap-time) relative to the other vehicle, as well as the standard deviation of the rate changes of the accelerator pedal and brake pedal to determine whether the driver is aggressive or cautious. The driver index value from fuzzy computation

and rule evaluation may determine the aggressiveness of the driver based on car following, vehicle speed and the driver's control actions on acceleration and deceleration.

For real-time vehicle implementation, the recursive estimation of the mean and variance of a variable of interest is applied. The signal conditioned average mean gap-time at sample time k can be computed as

$$g_k = g_{k-1} + \alpha\left(\Delta_{s_k} / v_{fk} - g_{k-1}\right) \tag{24}$$

where Δs_k is the relative distance between the leading and following vehicle, and v_{fk} is the velocity of the following vehicle. α is a filter coefficient similar to the one used in (22). Figures 13A and 13B show the mean gap-times computed from two runs of vehicle testing: one for aggressive driving and the other for cautious driving.

The acceleration pedal rate mean can be computed as

$$\overline{\rho}_k = \overline{\rho}_{k-1} + \alpha\left((\rho_k - \rho_{k-1})/\Delta T - \overline{p}_{k-1}\right) \tag{25}$$

where $\overline{\rho}$ is the acceleration pedal mean and ΔT is the sample time. The corresponding variance can be computed as

$$\upsilon_k \alpha \upsilon_{k-1} + (1-\alpha)(\rho_k - \overline{\rho}_k)^2 \tag{26}$$

and the standard deviation is obtained from the square-root of the variance. Figures 14A and 14B show the

standard deviations of two runs of test data for aggressive and cautious driving.

Similar to (25) and (26), the mean and variance of the brake pedal rate change can be computed. Figures 15A and 15B show the standard deviations of two runs of test data for aggressive and cautious driving. The variables are first normalized before presenting them to the fuzzy inference system. The fuzzy sets and membership functions were determined for the features to transform the crisp inputs into fuzzy terms. The mean gap-time fuzzy set G_S is defined by

$$G_s = \{(g, \mu(g)) | \, g \in G\} \qquad (27)$$

where G is given by the bounded collection of gap-times g in the vehicle path. The gap-time membership function μ is chosen to be a Gaussian function.

A zero-order TS model was used to compute the driver index level. A normalized output scale from 0-1.0 represented the levels from cautious, to less aggressive, to aggressive driving behavior. The driver index is obtained from fuzzy computation and rule evaluation. Table 1 shows the rules used. Notice that a higher gap-time is relatively more safety conscious compared to a lower gap-time.

Table 1

Rules for driving behavior characterization

If gap-time is	If accel pedal rate STD is	If brake pedal rate STD is	Then driver index is
Low	Low	Low	Less Aggressive
High	Low	Low	Cautious
Low	High	Low	Aggressive
Low	Low	High	Aggressive
Low	High	High	Aggressive
High	High	High	Less Aggressive
High	Low	High	Cautious
High	High	Low	Less Aggressive

Figures 16A and 16B show the driver index computed from two runs of vehicle testing data: one for aggressive driving with a driver index greater than 0.8 and the other for cautious driving with a driver index less than 0.2.

VII. Supervised Driving Style Characterization

The car-following task requires the driver to maintain with the leading vehicle one of the following (i) a zero speed difference; (ii) a constant relative distance; and (iii) a constant relative gap-time defined by the division of the relative distance by the relative velocity.

A human driver may be modeled as a PD feedback controller. The closed loop system during a car following maneuver may be expressed as

$$\left(\ddot{x}_l - \ddot{x}_f - \ddot{\bar{x}}_g\right) = -c_v\left(\dot{x}_l - \dot{x}_f - \dot{\bar{x}}_g\right) - c_s\left(x_l - x_f - \bar{x}_g\right) \qquad (28)$$

where x_l and x_f are the leading and the following vehicle travel distance and $\bar{x}_g$ is the gap offset reference. Due to the implementation of radar used in vehicles equipped with adaptive cruise control function, the relative distance and velocity are measured and defined as

$$\Delta s = x_l - x_f, \Delta v = \dot{x}_l - \dot{x}_f \tag{29}$$

A vehicle equipped with stability controls has a longitudinal accelerometer with output α_x, which measures $\ddot{x}_f$. (28) can be further expressed as

$$\alpha_x = c_v\left(\Delta v - \dot{\bar{x}}_g\right) + c_s\left(\Delta s - \bar{x}_g\right) + \left(\ddot{x}_l - \ddot{\bar{x}}_g\right) \tag{30}$$

The unknown parameters c_V and c_S in (30) can be used to characterize a driver's control structure during a car following. Using the low-pass filtered Δs and Δv to replace the gap offset reference $\bar{x}_g$ and its derivative $\dot{\bar{x}}_g$, and considering the time delays, we have the following equations

$$\begin{aligned} &\alpha_{x_{k+i}} = c_v\left[\Delta s_k - \mu_k(\Delta s)\right] + c_s\left[\Delta v_k - \mu_k(\Delta v)\right] + w \\ &\begin{bmatrix} \mu_k(\Delta s) \\ \mu_k(\Delta v) \end{bmatrix} = (1-\alpha)\begin{bmatrix} \mu_{k-1}(\Delta s) \\ \mu_{k-1}(\Delta v) \end{bmatrix} + \alpha\begin{bmatrix} \Delta s_k \\ \Delta v_k \end{bmatrix} \end{aligned} \tag{31}$$

where subscript i in $\alpha_{x_{k+i}}$ reflects the time delay between the driver's braking/throttling actuation and the measured relative distance and velocity, and

acceleration, α is a low-pass filter coefficient similar to the one used in (22), and w is a high frequency uncertain signal that may be treated as white noise. Using a conditional least square identification algorithm, c_v and c_s can be identified in real-time from (31). The response time t_p and the damping ratio ζ of the driver-in-the-loop system can be related to c_v and c_s as

$$t_p = 2\pi c_s / \sqrt{4c_s - c_c^2},\ \varsigma = c_v / 2\sqrt{c_s} \qquad (32)$$

which can be used to deduce the driver's driving behavior: (i) for a normal driver, it is desired that the transient response of the driver-in-the-loop system be fast (sufficiently small t_p, *e.g.*, less than 0.5 s) and damped (sufficiently large ζ); (ii) for an aged or driver with physical limitation, t_p may be large; (iii) for an aggressive driver, ζ is likely to show a small value, such as one less than 0.5, and the system response is likely to exhibit excessive overshoot; (iv) for a cautious driver, ζ is likely to show a reasonably large value, such as one greater than 0.7.

A least-square parameter identification was implemented for calculating c_v and c_s. Two runs of vehicle testing were conducted. In the 1st run, the driver in the following car tried to use aggressive throttling and braking to achieve a constant relative gap-time between his vehicle and a leading vehicle, which led to larger range error $\Delta s_k - \mu_k(\Delta s)$. *See*, Figure 17. The identified c_v is around 0.2 and identified c_s around 0.05. *See*, Figure 18. The damping ratio thus computed from (32) showed a value less than 0.5, which is an indication of a light

damping driver-in-the-loop system, hence corresponding to aggressive driving behavior.

In the 2nd run, the driver was using cautious throttle and brake application to achieve car following, the relative range error $\Delta s_k - \mu_k(\Delta s)$ in Figure 19 had less magnitude in comparison with the one shown in Figure 17. The identified c_v and c_s are depicted in Figure 20. The damping ratio showed a value greater than 0.8 except during the first 150 seconds. *See*, Figure 20. This is an indication of a heavy damping driver-in-the-loop system, hence corresponding to cautious driving behavior.

VIII. Applications

The handling limit and/or driving style characterization, with proper monitoring and re-enforcement, may be used for driver advising, coaching, monitoring and safety enforcement. Another possible application relates to the opportunity for vehicle personalization through tuning of control parameters to fit the specific driver's style. For example, the ESC or brake control system can exploit such a driver style characterization to adapt the actuation threshold to fit the personal driving behavior. As an example, an expert driver might need less frequent ESC activations compared to a less experienced driver in facing the same driving conditions. (There may, however, be a minimum requirement for adjusting the thresholds such that a mistake by an expert driver can still be assisted by the ESC function).

As another example, steering sensitivity (the degree of vehicle steering response to a given steering input) and accelerator pedal sensitivity (the degree of vehicle acceleration response to a given accelerator

pedal input) may be tuned based on the driver characterization. The steering wheel and/or accelerator pedal may be made more sensitive if the driver is characterized as an expert (providing greater vehicle responsiveness). The steering wheel and/or accelerator pedal may be made less sensitive if the driver is characterized as cautious (potentially leading to improved fuel economy). Other applications are also possible.

Figure 21 is a block diagram of an embodiment of an advisory system 30 for a vehicle 32. The advisory system 30 may include a plurality of vehicle state sensors 34 (e.g., yaw rate sensor, steering angle sensor, lateral acceleration sensor, longitudinal acceleration sensor, wheel speed sensor, brake pressure sensor, *etc.*), one or more controllers 36 configured to perform, for example, electronic stability control, anti-lock braking and traction control as well as the handling limit and driver characterization described above, an audio and/or visual indicator system 38 (*e.g.*, a display panel, speaker system, LED array, USB port, *etc.*), and a vehicle input and/or control system 40 (*e.g.*, accelerator pedal, powertrain controller, steering wheel, *etc.*)

The vehicle state sensors 34 may detect the various parameters described above, such as vehicle speed, wheel slip, *etc.*, that characterize the motion of the vehicle 32 (*e.g.*, current handling condition and limit handling condition) as well as the driver inputs described above (*e.g.*, accelerator and brake pedal position, *etc.*) The one or more controllers 36 may use this information as inputs to the handling limit and/or driver characterization algorithms described above. Based

on the output of these algorithms, the one or more controllers 36, as described above, may (i) activate the audio and/or visual indicator system 38 to, for example, alert or coach the driver or (ii) modify aspects of the vehicle input and/or control system 40 to customize the vehicle's response to the type of driver.

As an example, based on information gathered by the sensors 34, the one or more controllers 36, executing the algorithms described above, may determine that a driver of the vehicle 32 is driving recklessly. Because the driver has been classified as reckless, the one or more controllers 36 may, for example, begin to issue driving instructions via the audio and/or visual indicator system 38 to encourage the driver to change their behavior. The one or more controllers 36 may also/instead activate haptic elements of the vehicle input and/or control system 40, such as a haptic accelerator pedal, to alert the driver of their reckless behavior.

A memory accessible by the one or more controllers 36 may include a database of instructions (audio and/or visual) that are mapped with certain predefined rules. An example rule may be that if a driver is reckless and the rate of steering wheel angle change falls within some defined range for a specified period of time (that is, the driver continues to rapidly rotate the steering wheel clockwise and counterclockwise), then instruct the driver to reduce their steering inputs.

Figure 22 is a block diagram of another embodiment of an advisory system 130 for a vehicle 132, where like numerals have descriptions similar to those of Figure 21. In this embodiment, however, the vehicle 132

includes a token recognition system 142 configured in a known fashion to recognize a token 144. As an example, the token 144 may be a key including an identification chip identifying a particular driver or class of drivers (*e.g.*, teen drivers). In this example, the token recognition system 142 may include a chip reader arranged in a known fashion within an ignition system of the vehicle 132 to read the identification chip and communicate this information to the one or more controllers 136. As another example, the token 144 may be a key-fob or plastic card having an RFID chip embedded therein. In this example, the token recognition system 142 may include an RFID chip reader arranged in a known fashion within the vehicle 132 to detect and read the RFID chip and communicate this information to the one or more controllers 136. As yet another example, the token 144 may be a cell phone. In this example, the token recognition system 142 may include known modules (such as Ford's SYNC technology) configured to recognize the cell phone and communicate this information to the one or more controllers 136. Other arrangements and scenarios are also possible.

A variety of functions may be implemented based on driver identification and the handling limit and/or driving style characterization described above. As an example, if the token recognition system 142 supplies information to the one or more controllers 136 identifying the driver as a teen driver, the one or more controllers 136 may issue instructions to the driver via the audio and/or visual indicator system 138 to drop throttle or to brake as the handling limit is being approached. The one or more controllers 136 may implement

rule based commands similar to those described above to effectuate such driving instruction. (An example rule may be that if the driver is a teen driver and if the handling limit margin is less than 15%, then instruct the driver to slow down.)

As another example, if the token recognition system 142 supplies information to the one or more controllers 136 identifying the driver as a teen driver, the one or more controllers 136 may record a history of the calculations of handling limit margin and/or driver style characterization in order to generate reports describing driving behavior. These reports, for example, may detail, for a given trip, the number of times the teen driver exceeded certain levels of the handling limit margin. These reports, for example, may also describe the teen driver as cautious, aggressive, reckless, *etc.* during any given trip. Such reports may be accessed, reported or displayed in any suitable/known fashion, such as through the audio and/or visual indicator system 138.

As yet another example, driver coaching and/or instruction may be implemented based on the driver identification described above. The one or more controllers 136 may, for example, issue instructions to encourage a driver to provide driving inputs to the vehicle 132 that will result in the driver being classified as cautious. If, for example, a driver begins to frequently accelerate and decelerate, the one or more controllers 136 may instruct the driver via the audio and/or visual indicator system 138 to increase the distance between the vehicle 132 and vehicle in front of them so as to reduce the frequency of acceleration and braking. Rules similar to those described above, or any

other suitable intelligence technology such as neural networks, *etc.* may be used to facilitate the instructions. In embodiments where driving behavior is recorded for later reporting, whether the driver heeds or ignores the instructions may also be recorded as an indication of the driver's behavior.

Figure 23 is a block diagram of yet another embodiment of an advisory system 230 for a vehicle 232, where like numerals have descriptions similar to those of Figure 21. This embodiment includes a radar and/or camera system 246 (any suitable forward sensing system, however, may be used) that may periodically/continuously detect, in a known fashion, the distance between the vehicle 232 and another vehicle in front of the vehicle 232. (Although not shown, the advisory system 230 may also include a token recognition system and associated capabilities similar to that discussed with reference to Figure 22. Other configurations are also possible.)

In certain circumstances, the distance information collected by the system 246 may be monitored by the one or more controllers 236. If the distance is less than some predefined threshold (*e.g.*, 20 feet), the one or more controllers 236 may warn the driver via the audio and/or video indicator system 238 and/or activate elements of the vehicle input and/or control systems 240 if they are of the haptic type (*e.g.*, haptic accelerator pedal, haptic steering wheel, haptic seat, *etc.*)

In other circumstances, the distance information, X, collected by the system 246, together with the change in distance over time, V_x, and longitudinal acceleration of the vehicle 232, A_x, may used by the one or more controllers 236 to determine a time to

collision, t_C, with the vehicle in front of the vehicle 232 by the following equation

$$t_c = \frac{-V_x \pm \sqrt{(V_x)^2 + 2(A_x)(X)}}{(A_x)}$$

$$or \qquad t_c = \frac{X}{V_x}$$

If the time to collision is less than a predefined threshold, the one or more controllers 236 may warn the driver as described above.

In still other circumstances, the one or more controllers 236 may base the warning threshold on the gap time (discussed above) between the vehicle 232 and the vehicle in front of it. If the gap time is less than a threshold value, the one or more controllers 236 may, for example, activate (vibrate) haptic elements of the vehicle input and/or control systems 240, *etc*.

Alternatively, the one or more controllers 236 may access tables of distance and speed/relative speed to determine when to warn the driver. As an example, if the distance falls within a certain range and the speed falls within a certain range, the one or more controllers 236 may activate a haptic accelerator pedal. Other scenarios are also possible.

The intensity (frequency and/or amplitude) with which haptic elements of the vehicle input and/or control systems 240 are activated may depend on the distance, time to collision, gap time, *etc*. between the vehicle 232 and the vehicle in front of it. As an example, the intensity may increase as these parameters decrease. This increasing intensity may signal increasing urgency.

The predefined thresholds may depend on the type of driver. That is, the one or more controllers 236 may implement the driver characterization algorithms discussed above and, based on the characterization, increase or decrease the warning threshold. A threshold may be decreased, for example, for an expert driver because they may be less likely to experience an accident as a result of tailgating. A threshold may be increased for a reckless or aggressive driver because they may be more likely to experience an accident as a result of tailgating, etc.

The predefined thresholds may be altered based on whether the driver heeds the warning they indicate. As an example, if a driver does not increase their following distance to the vehicle in front of them after activation of a haptic accelerator pedal, the predefined following distance that is used to trigger the activation of the haptic pedal may be decreased so as to avoid becoming a nuisance to the driver. The predefined thresholds associated with time to collision and gap time may be similarly decreased. A minimum, however, may be established beyond which the threshold will not be decreased.

As apparent to those of ordinary skill, the algorithms disclosed herein may be deliverable to a processing device, which may include any existing electronic control unit or dedicated electronic control unit, in many forms including, but not limited to, information permanently stored on non-writable storage media such as ROM devices and information alterably stored on writeable storage media such as floppy disks, magnetic tapes, CDs, RAM devices, and other magnetic and

optical media. The algorithms may also be implemented in a software executable object. Alternatively, the algorithms may be embodied in whole or in part using suitable hardware components, such as Application Specific Integrated Circuits (ASICs), state machines, controllers or other hardware components or devices, or a combination of hardware, software and firmware components.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. The words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention.

WHAT IS CLAIMED:

1. A vehicle comprising:

at least one of an electronic stability control system, anti-lock braking system and traction control system;

a plurality of sensors configured to measure parameters representing the vehicle's current handling condition and the vehicle's limit handling condition, wherein each of the parameters has upper and lower deadband thresholds defining a deadband interval within which the measured parameter may fall without the at least one electronic stability control system, anti-lock braking system and traction control system being activated; and

at least one computing device operatively arranged with the sensors and configured (i) to determine, for each of the parameters, a normalized difference between the parameter and at least one of the parameter's upper and lower deadband thresholds, (ii) to identify a minimum of the normalized differences, and (iii) to initiate an alert for a driver of the vehicle if the minimum of the normalized differences exceeds a predetermined threshold within the deadband interval.

2. The vehicle of claim 1 further comprising a haptic pedal, wherein initiating an alert for a driver of the vehicle includes activating the haptic pedal.

3. The vehicle of claim 1 further comprising at least one of an audio, visual and haptic driver interface operatively arranged with the at least one

computing device, wherein initiating an alert for the driver includes activating the at least one of audio, visual and haptic driver interface.

4. The vehicle of claim 1 wherein the sensors include at least one of a yaw rate sensor, steering angle sensor, lateral acceleration sensor, longitudinal acceleration sensor, wheel speed sensor, and brake pressure sensor.

5. The vehicle of claim 1 wherein the computing device is further configured to low-pass filter the minimum of the normalized differences.

6. A method for advising a driver of a vehicle comprising:

measuring a plurality of parameters representing the vehicle's current handling condition and the vehicle's limit handling condition;

determining a margin between the vehicle's current handling condition and limit handling condition; and

initiating an alert for the driver before the vehicle achieves the limit handling condition if the margin exceeds a predetermined threshold.

7. The method of claim 6 wherein each of the parameters has upper and lower deadband thresholds defining a deadband interval within which the measured parameter may fall without initiating electronic stability control, anti-lock braking or traction control.

8. The method of claim 7 wherein determining a margin between the vehicle's current handling condition and limit handling condition includes, for each of the measured parameters, determining a normalized difference between the measured parameter and at least one of the measured parameter's upper and lower deadband thresholds.

9. The method of claim 8 wherein determining a margin between the vehicle's current handling condition and limit handling condition includes identifying a minimum of the normalized differences.

10. The method of claim 9 wherein determining a margin between the vehicle's current handling condition and limit handling condition includes low-pass filtering the minimum of the normalized differences.

11. The method of claim 6 wherein initiating an alert for the driver includes activating a haptic pedal.

12. The method of claim 6 wherein the alert is at least one of an audio, visual and tactile alert.

13. The method of claim 6 wherein the alert is a voice alert.

14. The method of claim 6 wherein the parameters include at least one of yaw rate, steering angle, lateral acceleration, longitudinal acceleration, wheel speed, and brake pressure.

15. The method of claim 6 further comprising characterizing a driver's dynamic control of the vehicle based on the margin.

16. The method of claim 15 further comprising altering the predetermined threshold based on the characterization.

17. An automotive vehicle comprising:

at least one of an electronic stability control system, anti-lock braking system and traction control system; and

at least one computing device configured to initiate an alert for a driver before the at least one of the electronic stability control system, anti-lock braking system and traction control system activates based on a margin between the vehicle's current handling condition and limit handling condition.

18. The vehicle of claim 17 wherein the at least one computing device is further configured to receive a plurality of parameter values representing the vehicle's current handling condition and limit handling condition.

19. The vehicle of claim 17 further comprising a driver interface operatively arranged with the at least one computing device, wherein initiating an alert for a driver includes activating the driver interface.

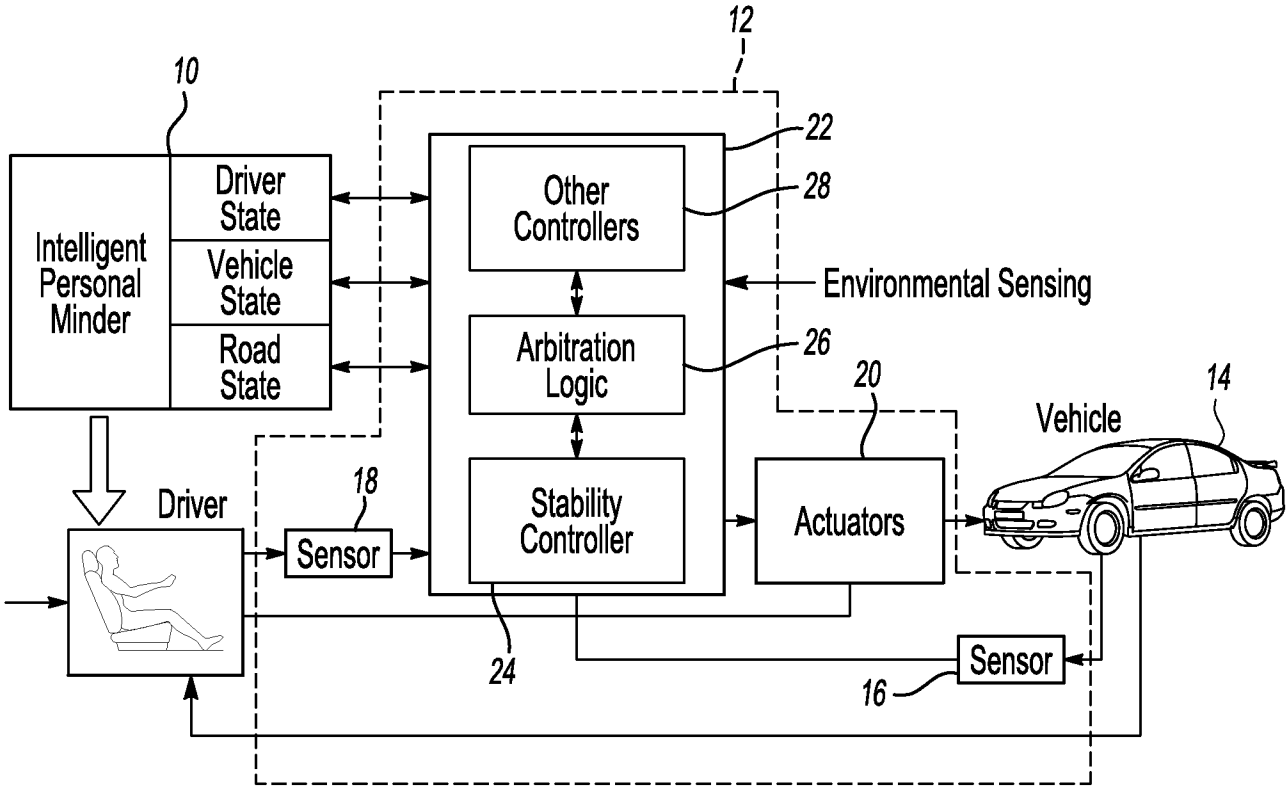

12
10
Intelligent Personal Minder
Driver State
Vehicle State
Road State
22
Other Controllers
28
Environmental Sensing
Arbitration Logic
26
20
14
Vehicle
Driver
18
Sensor
Stability Controller
Actuators
24
Sensor
16

Fig-1

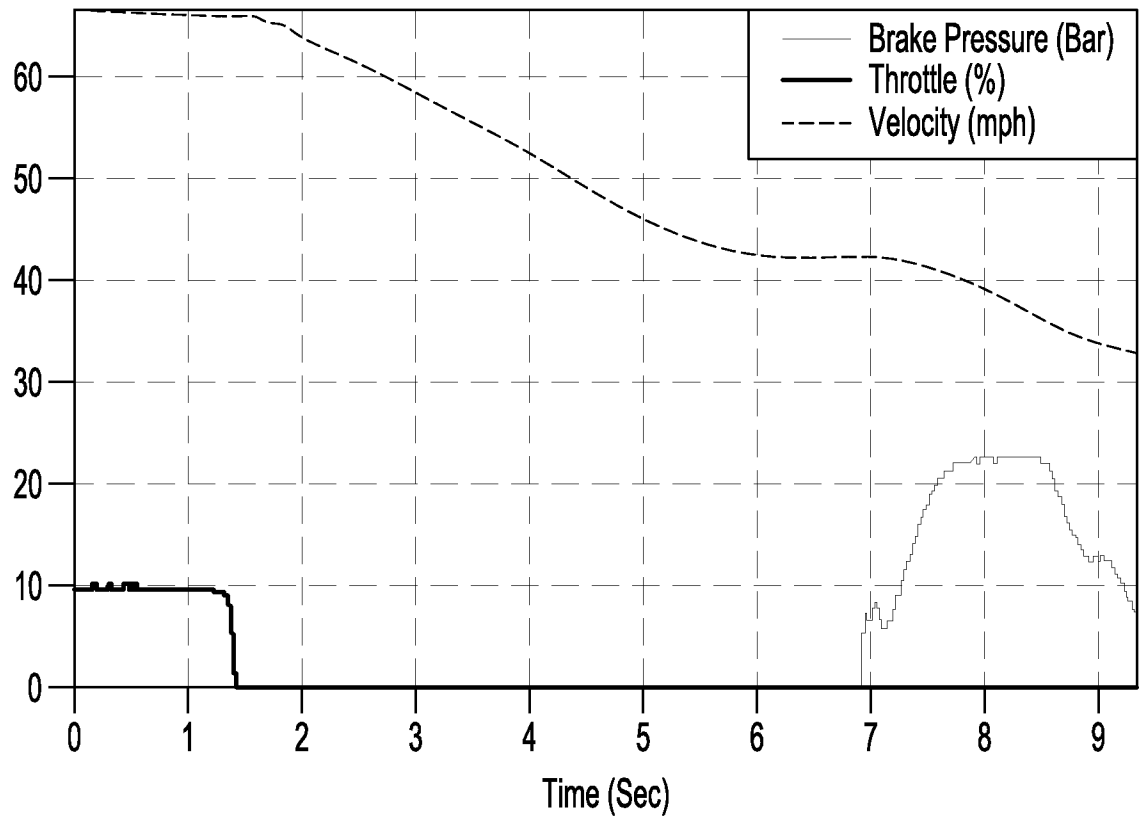

Brake Pressure (Bar)
Throttle (%)
Velocity (mph)
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
Time (Sec)

Fig-2

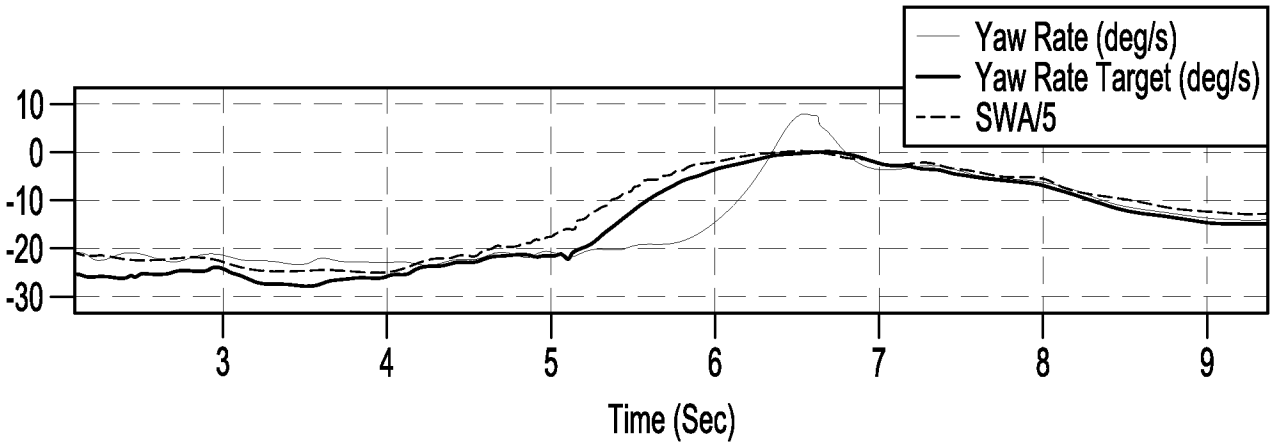


Fig-3A

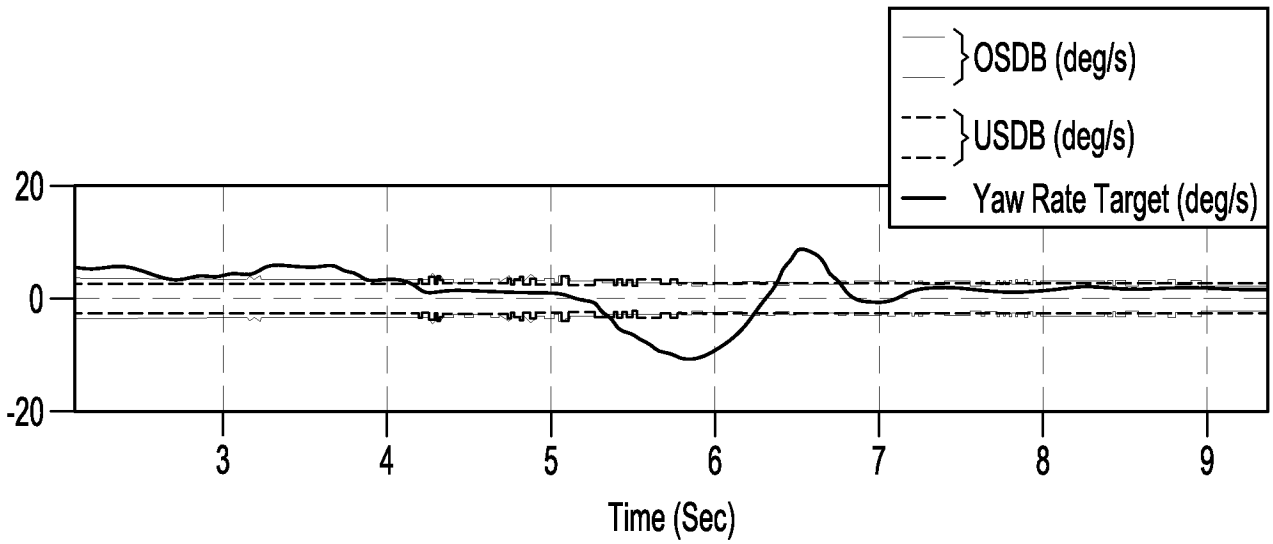


Fig-3B

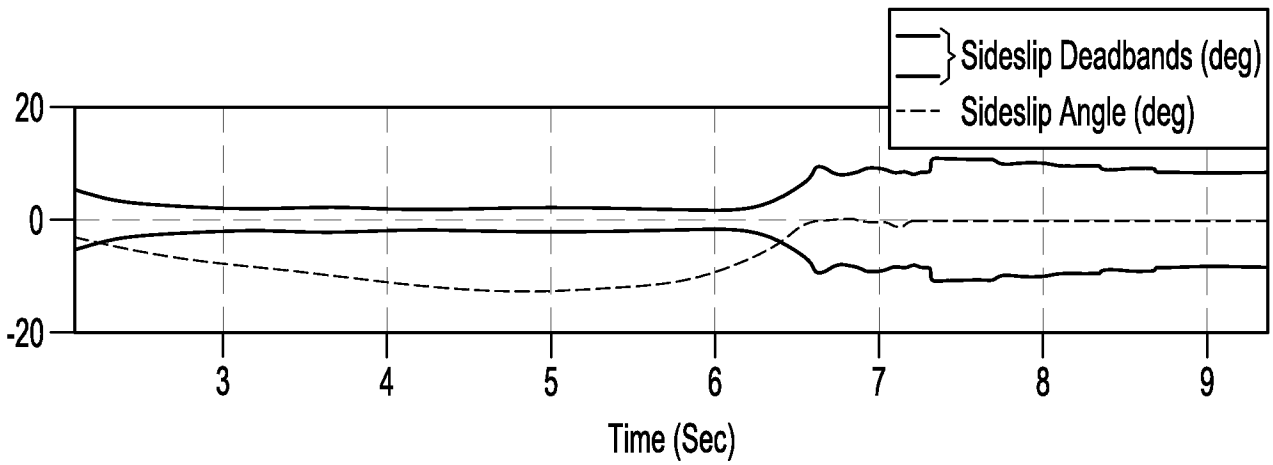


Fig-3C

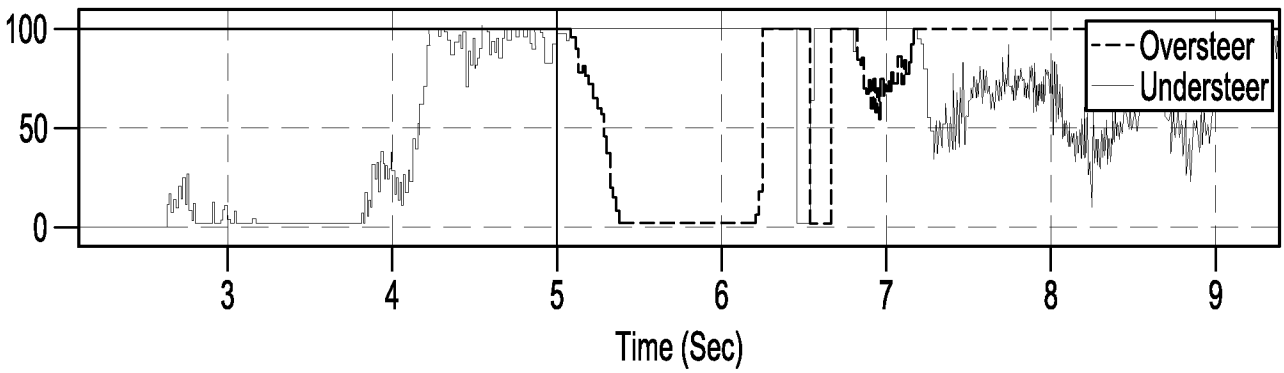


Fig-4A

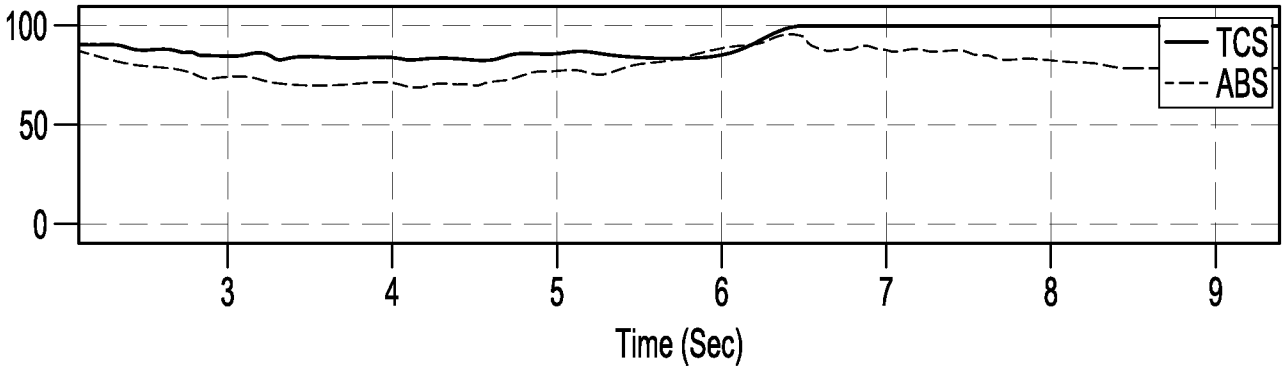


Fig-4B

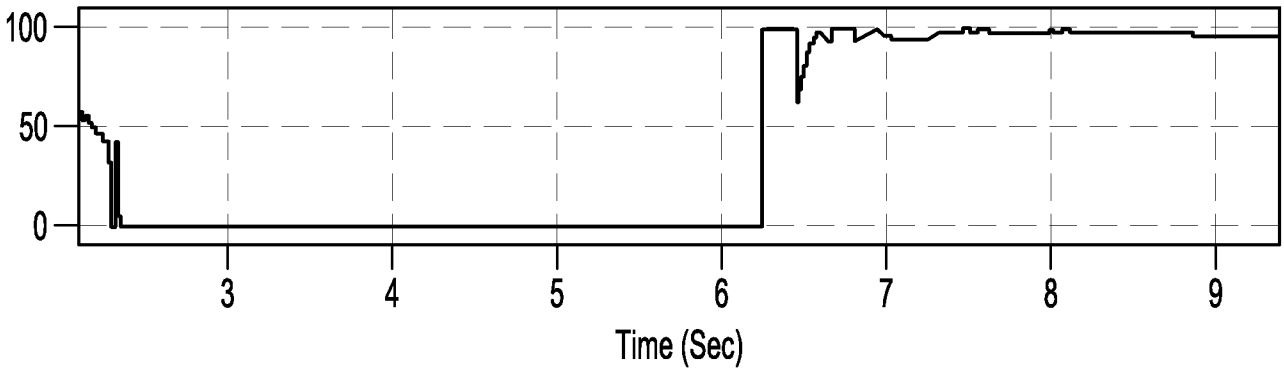


Fig-4C

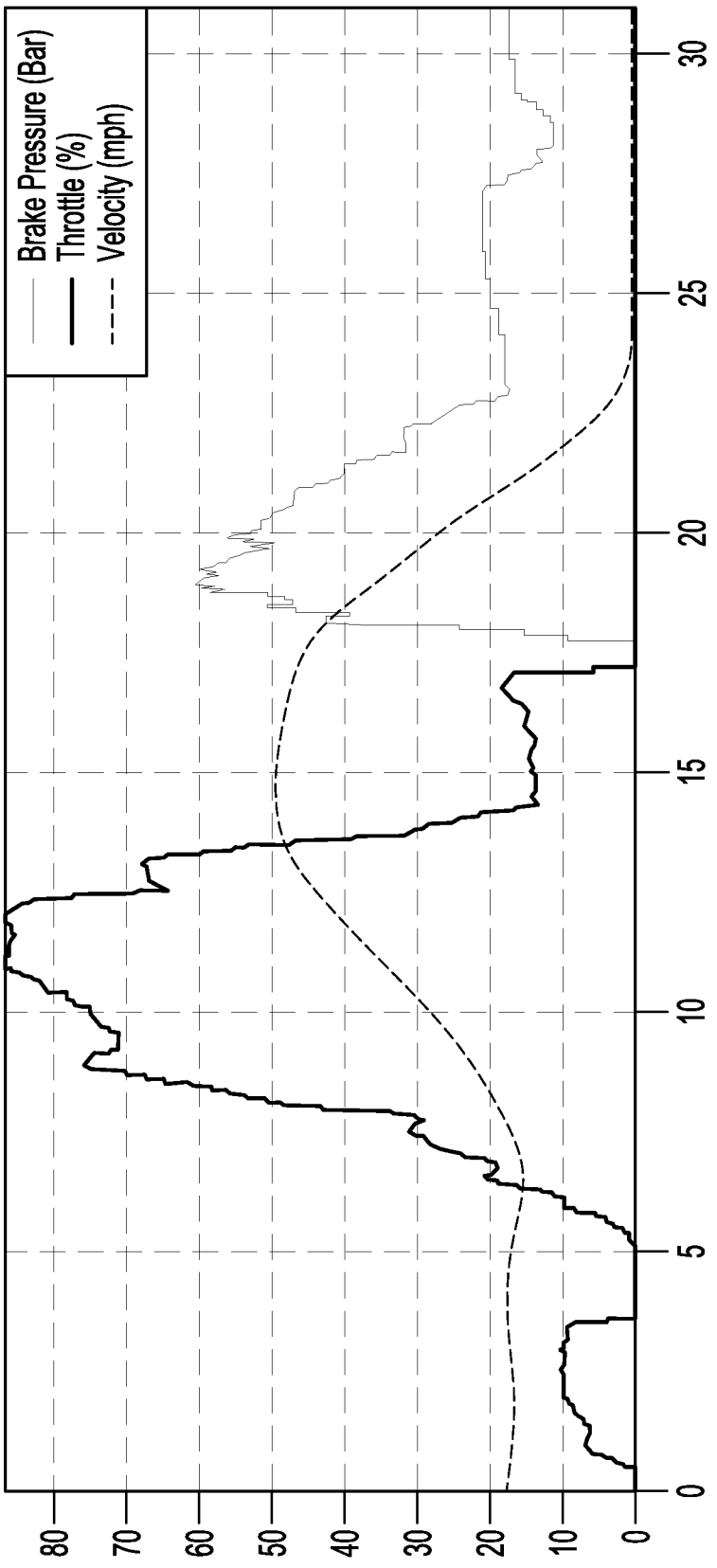

Brake Pressure (Bar)
Throttle (%)
Velocity (mph)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
Time (Sec)

Fig-5

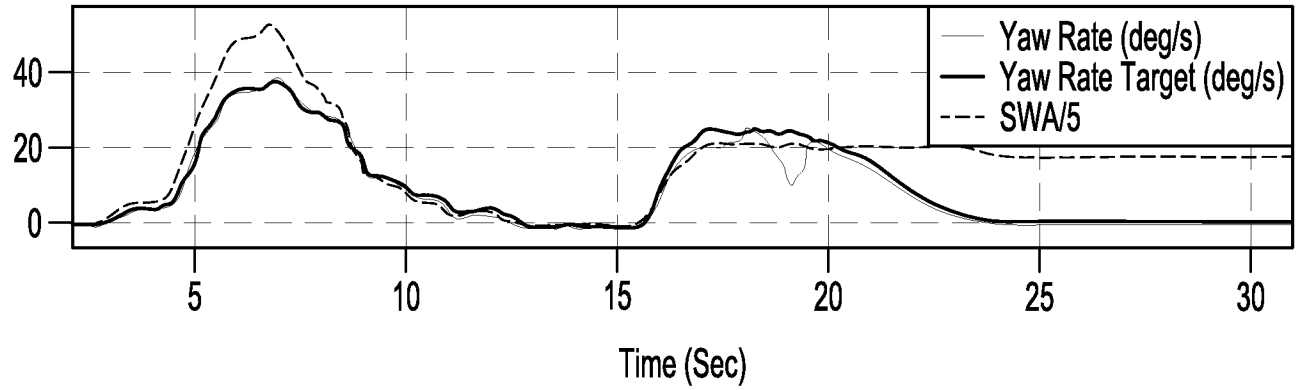


Fig-6A

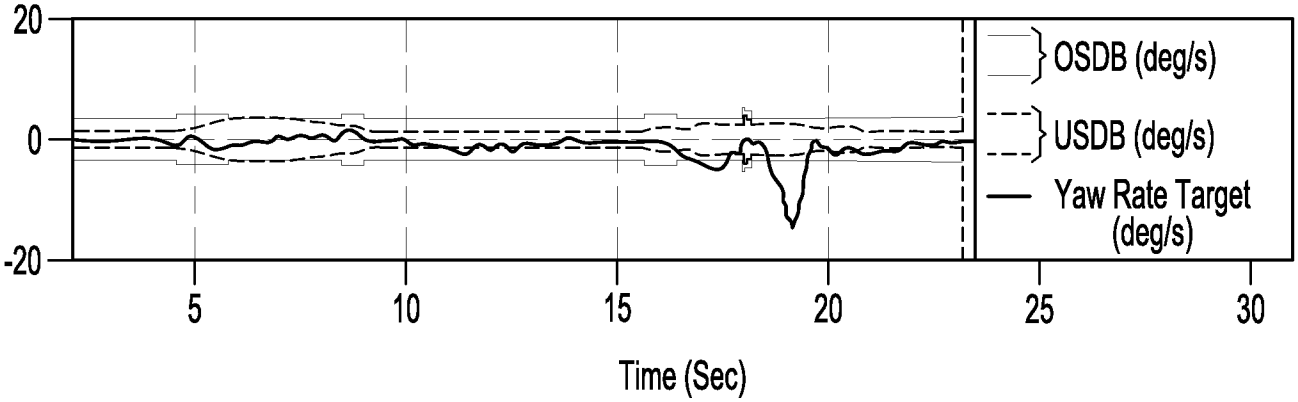


Fig-6B

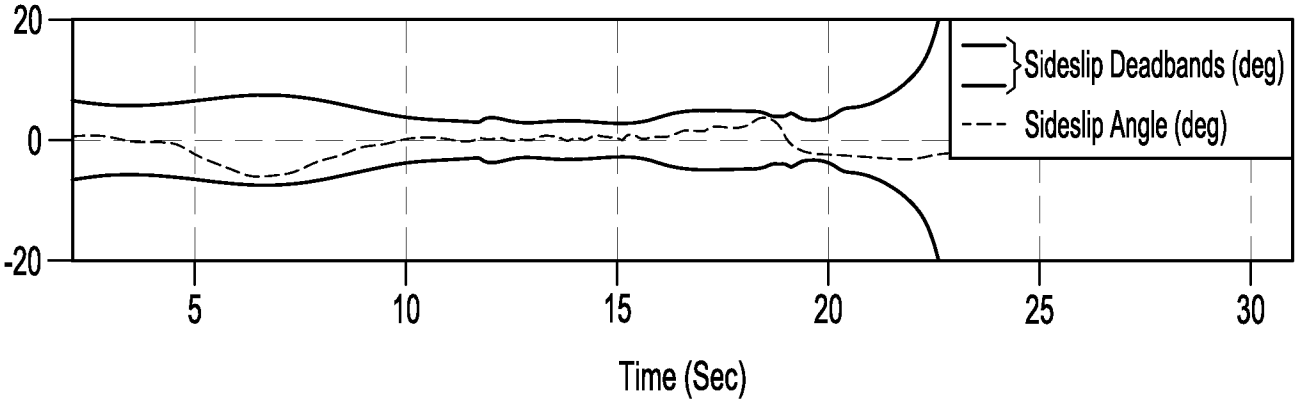


Fig-6C

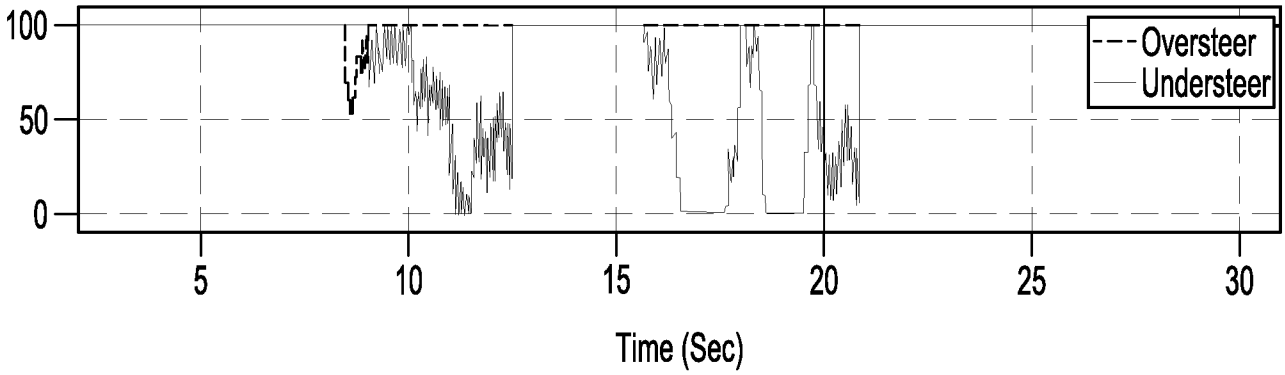


Fig-7A

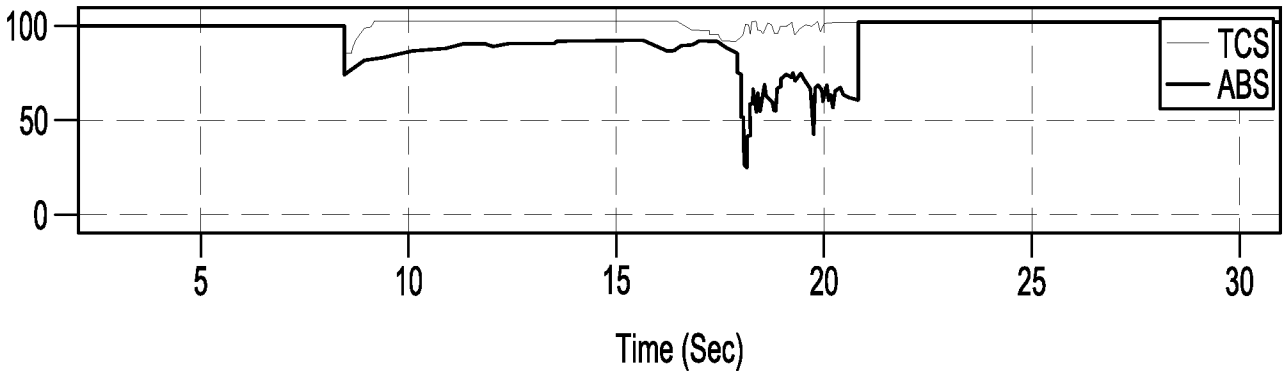


Fig-7B

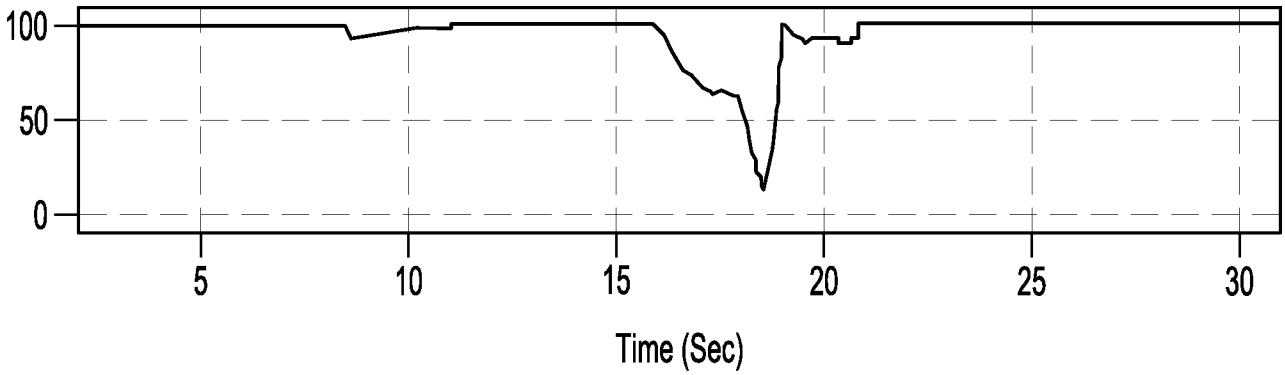


Fig-7C

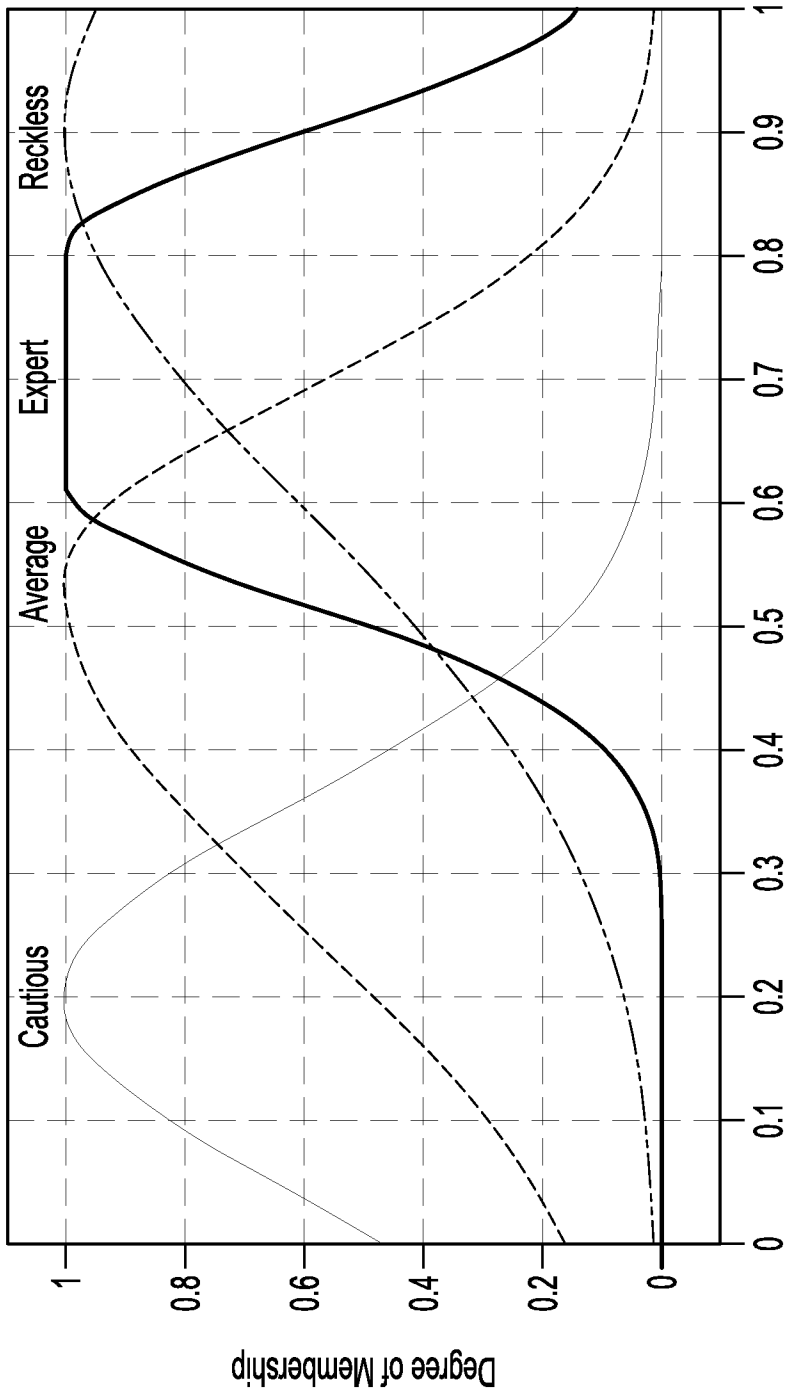

Degree of Membership
0
0.2
0.4
0.6
0.8
1
Cautious
Average
Expert
Reckless
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
% Violation

Fig-8

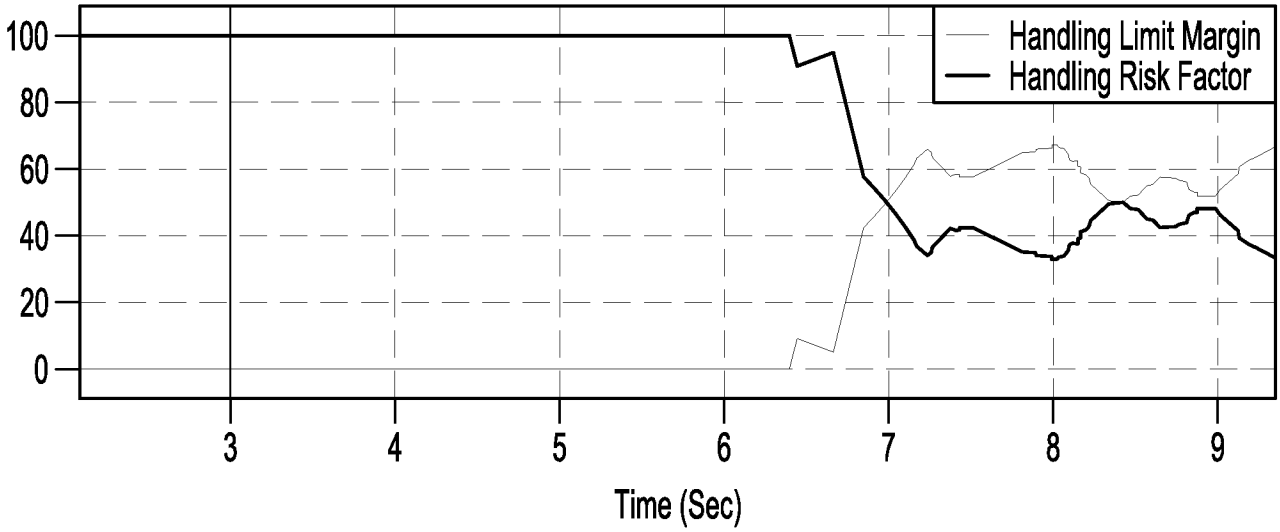

100
80
60
40
20
0
3
4
5
6
7
8
9
Time (Sec)
Handling Limit Margin
Handling Risk Factor

Fig-9A

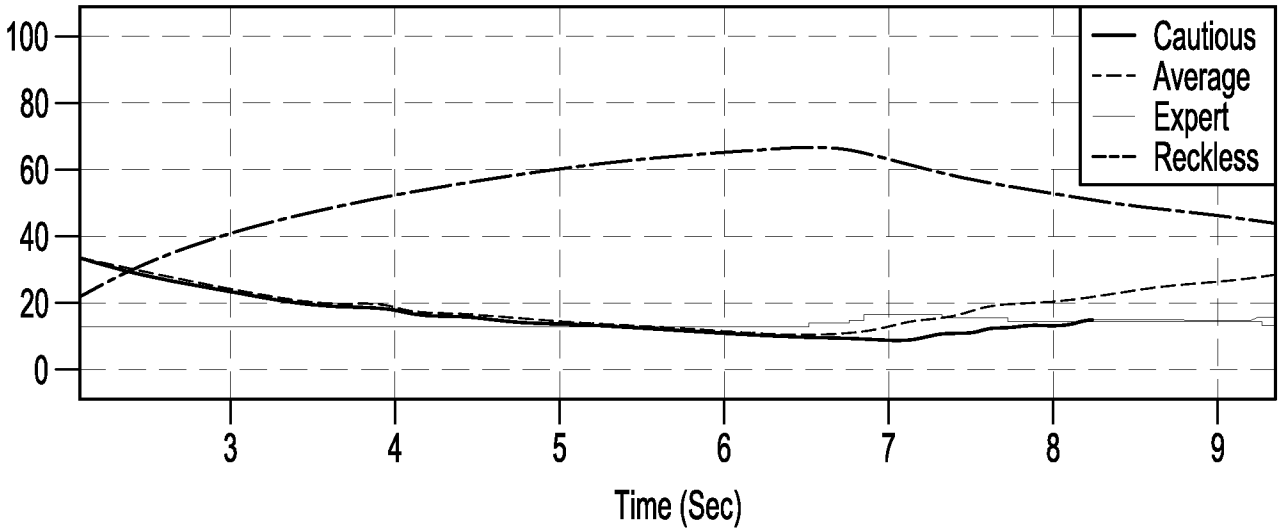

100
80
60
40
20
0
3
4
5
6
7
8
9
Time (Sec)
Cautious
Average
Expert
Reckless

Fig-9B

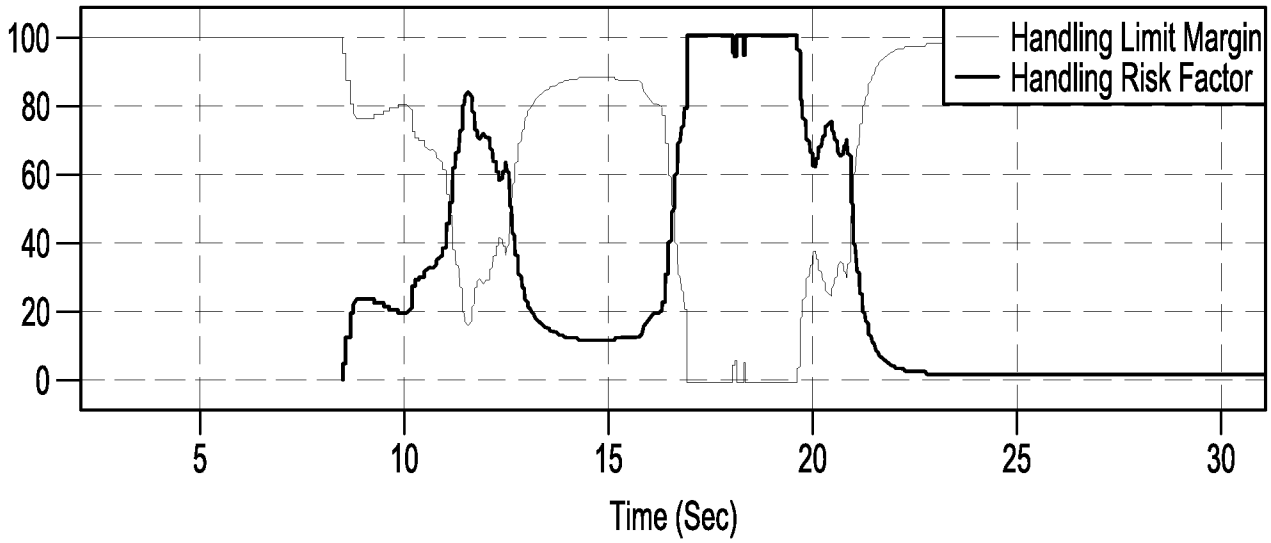


Fig-10A

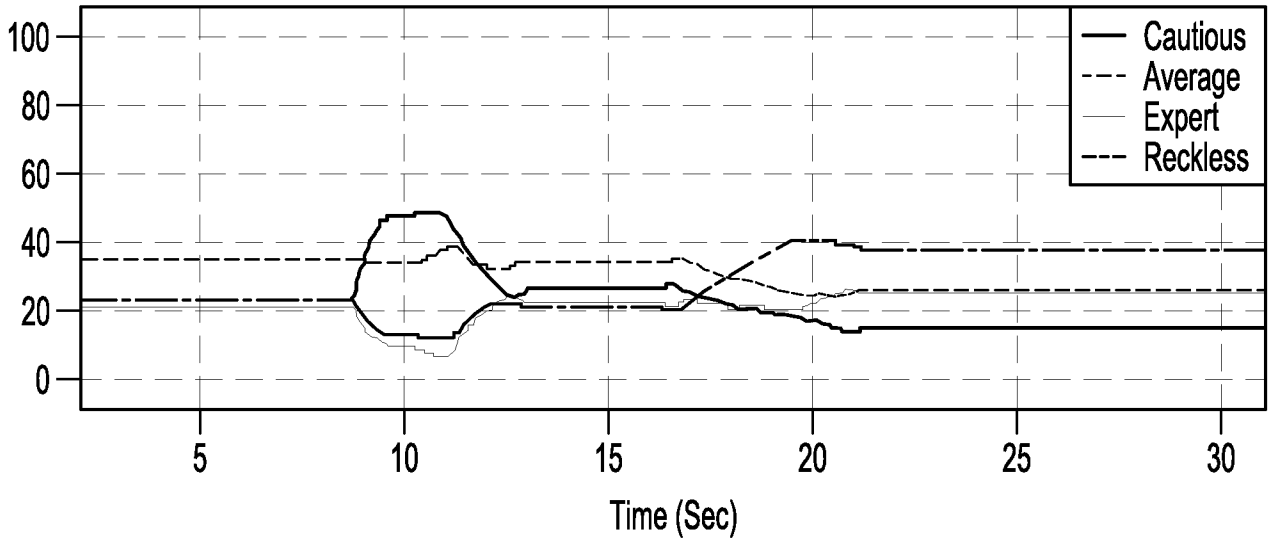


Fig-10B

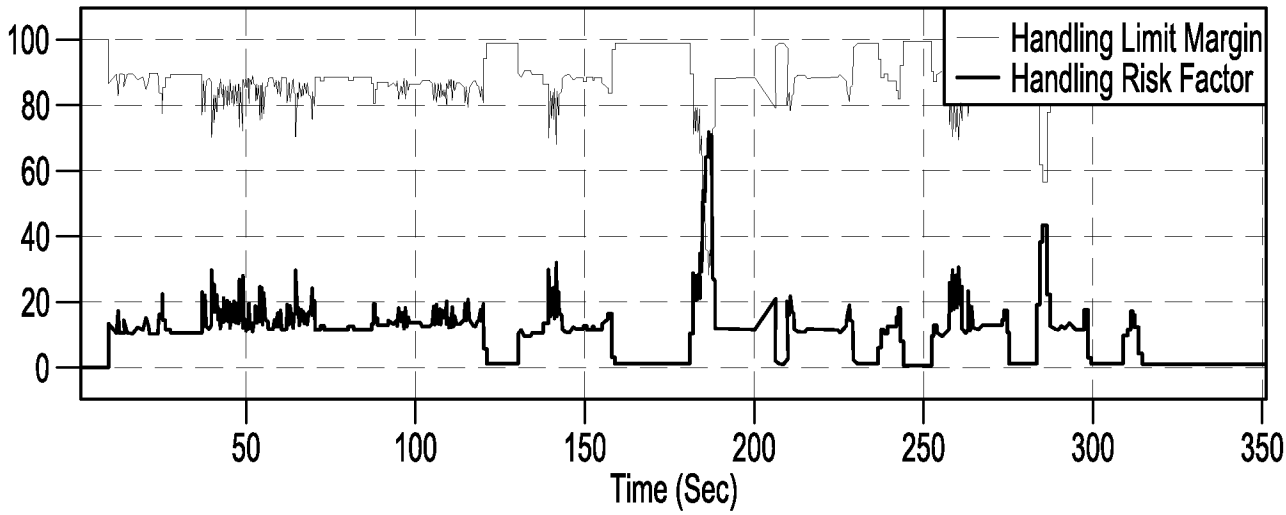


Fig-11A

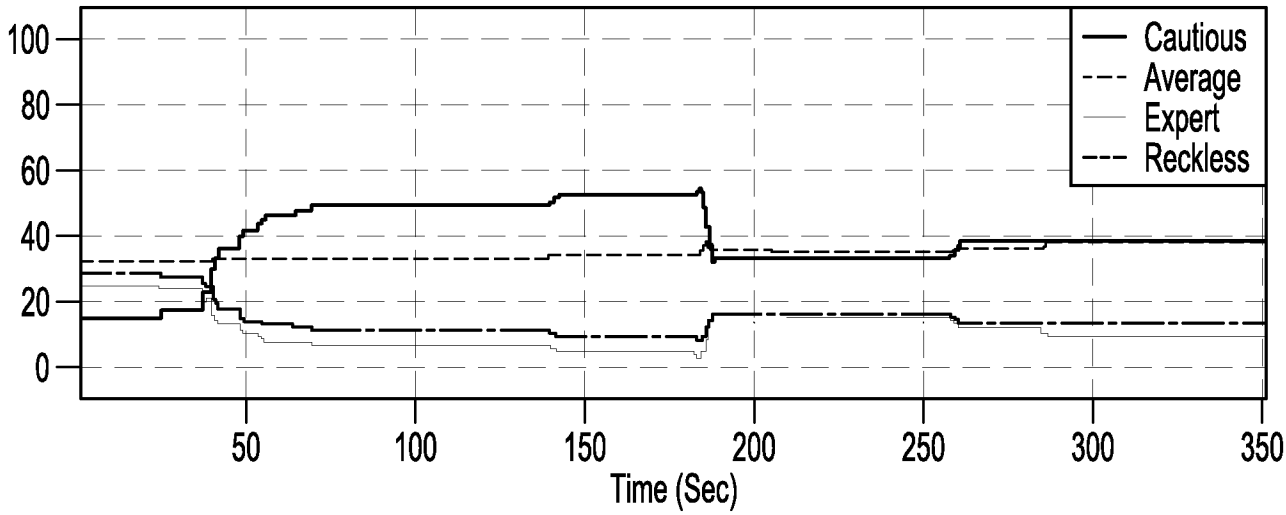


Fig-11B

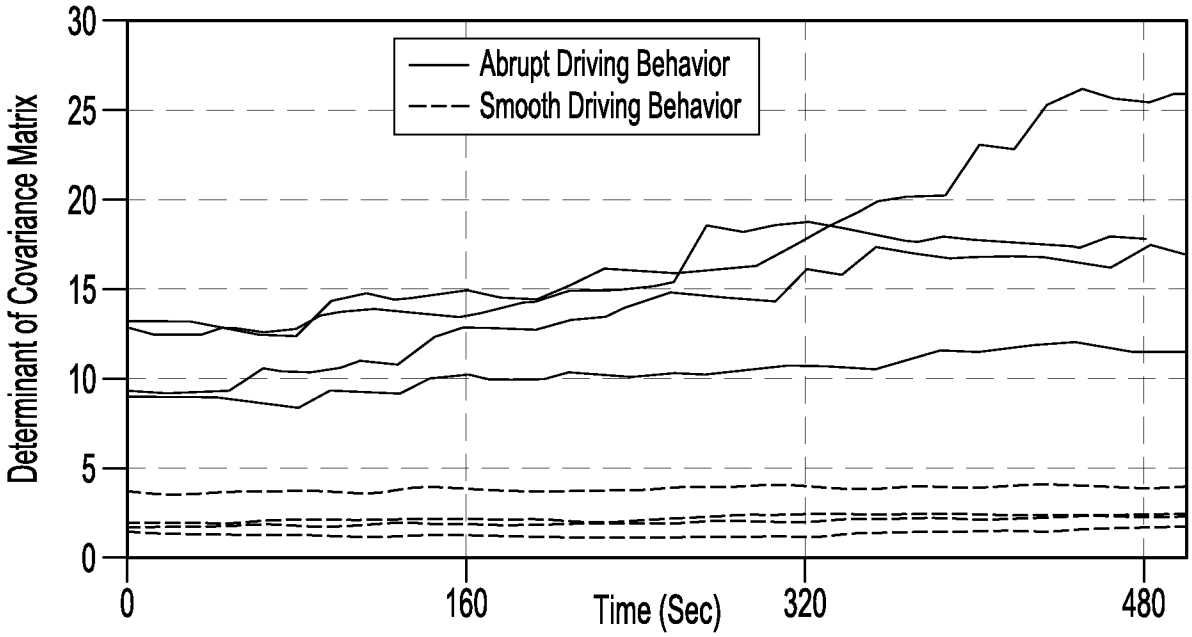


Fig-12

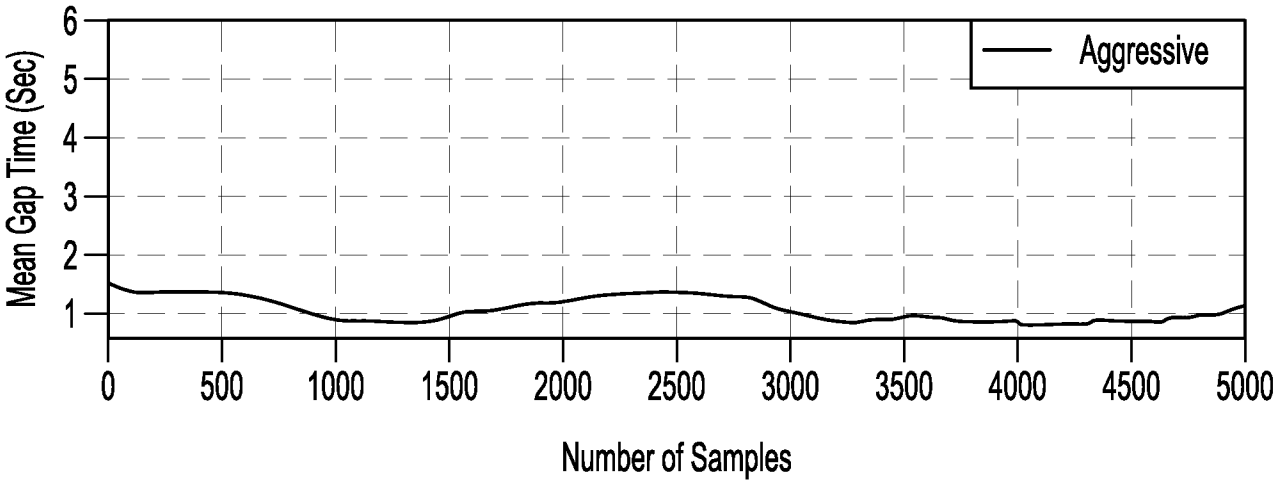


Fig-13A

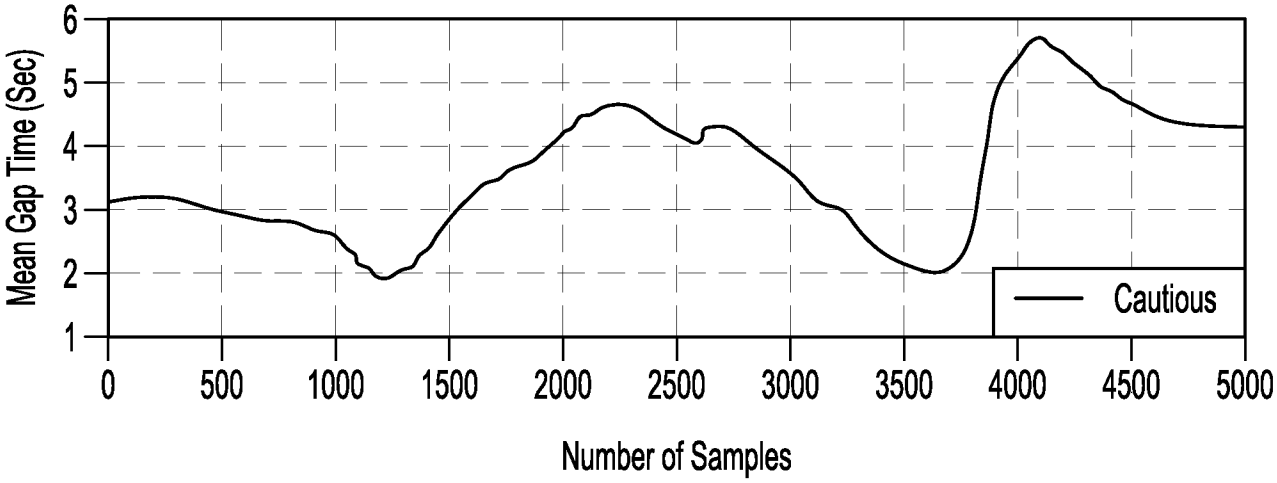


Fig-13B

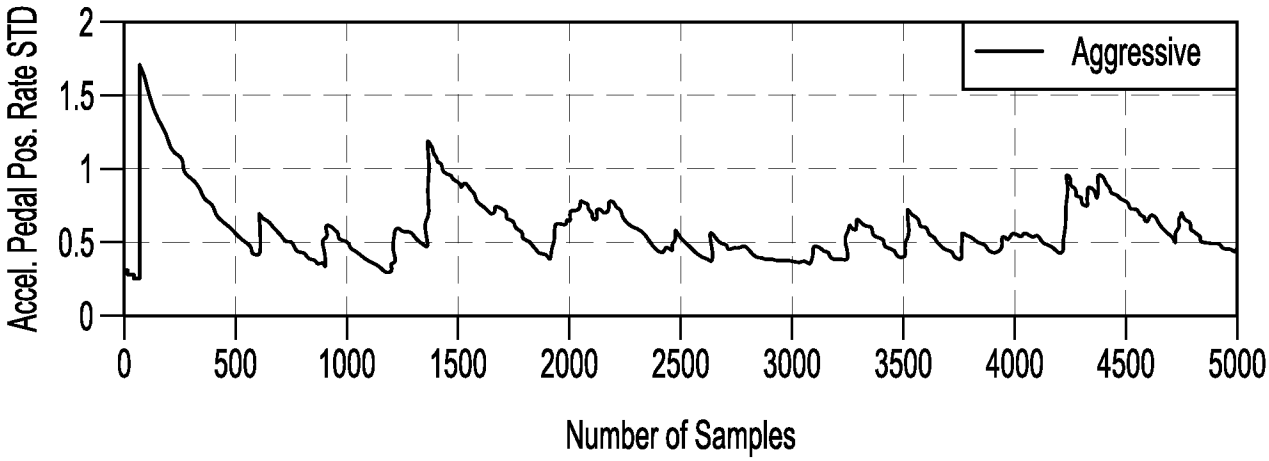


Fig-14A

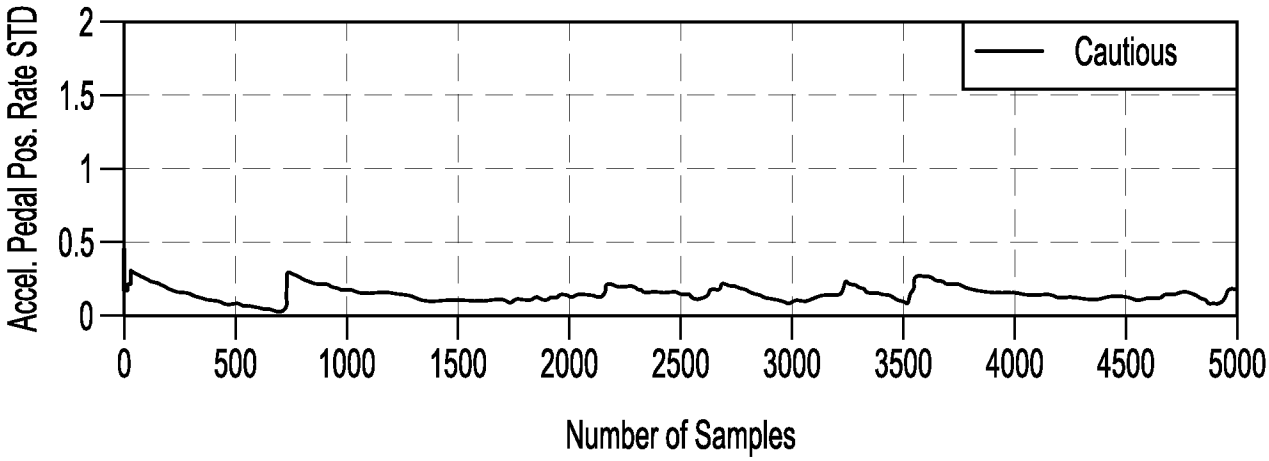


Fig-14B

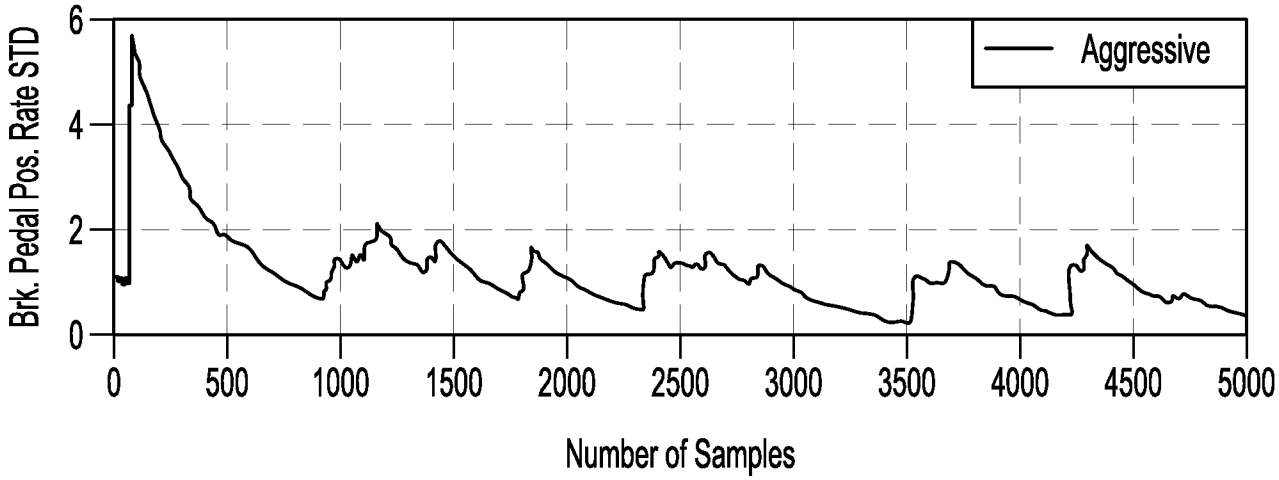


Fig-15A

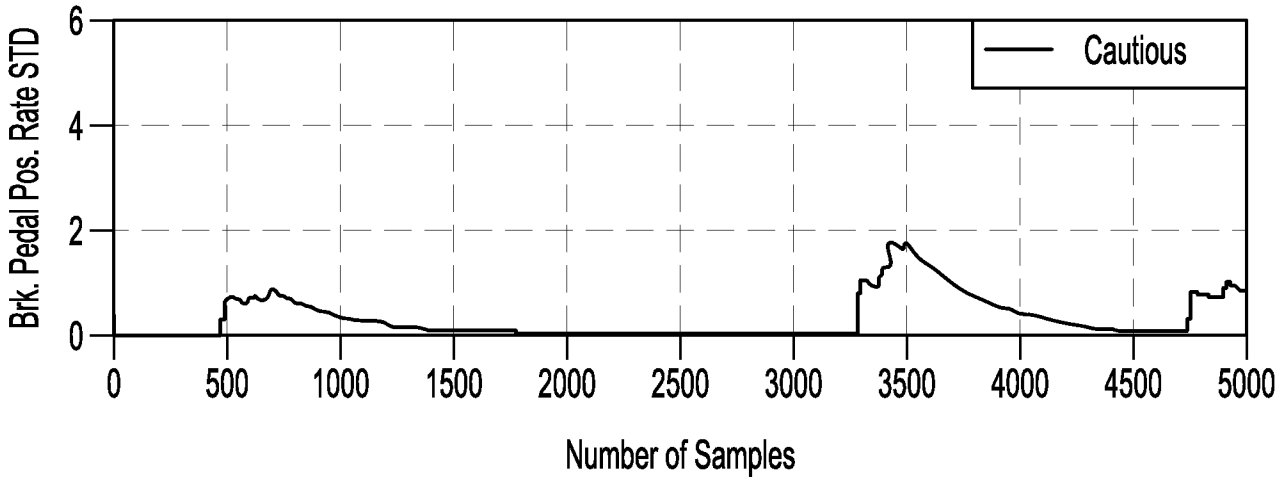


Fig-15B

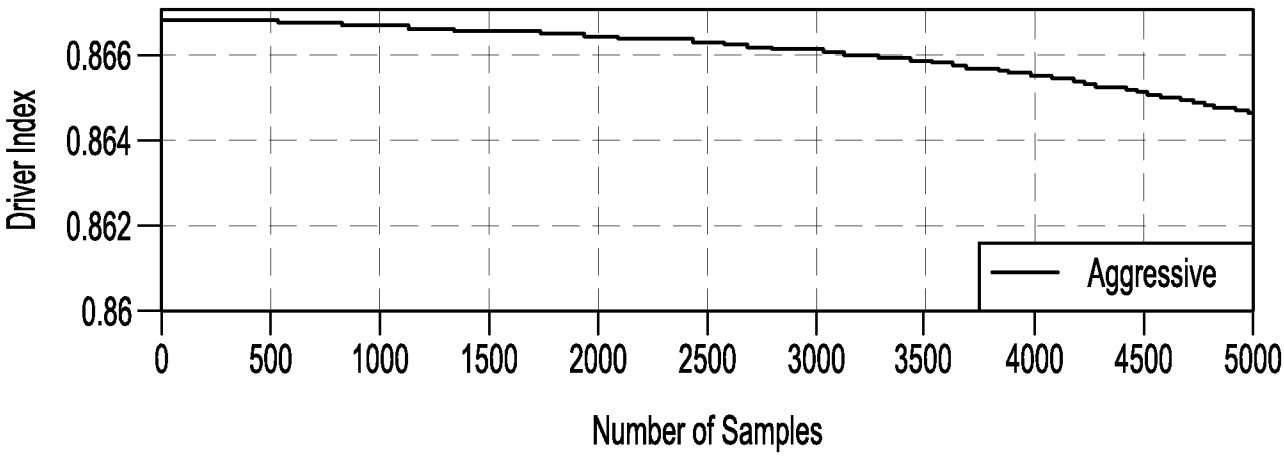


Fig-16A

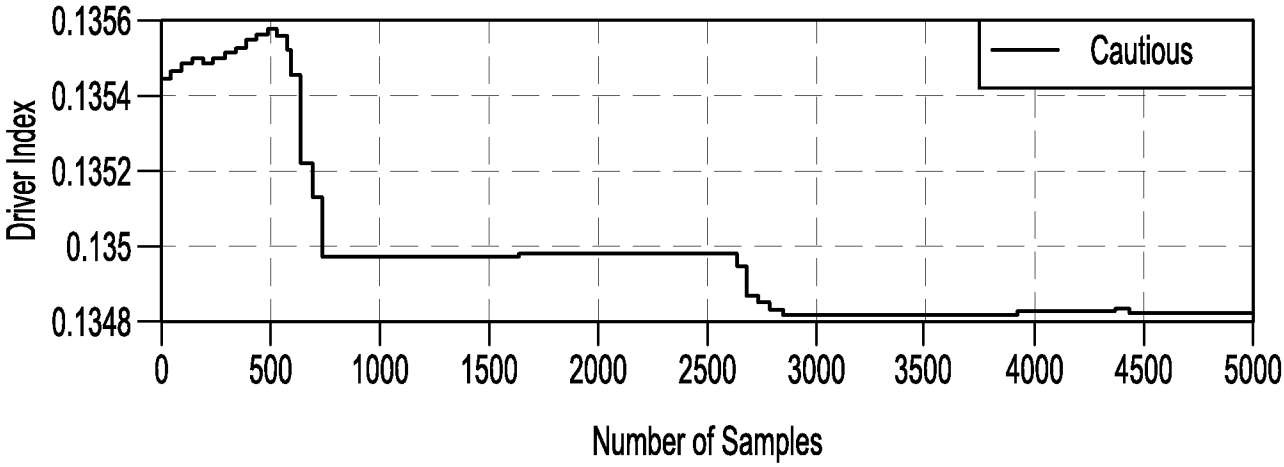


Fig-16B

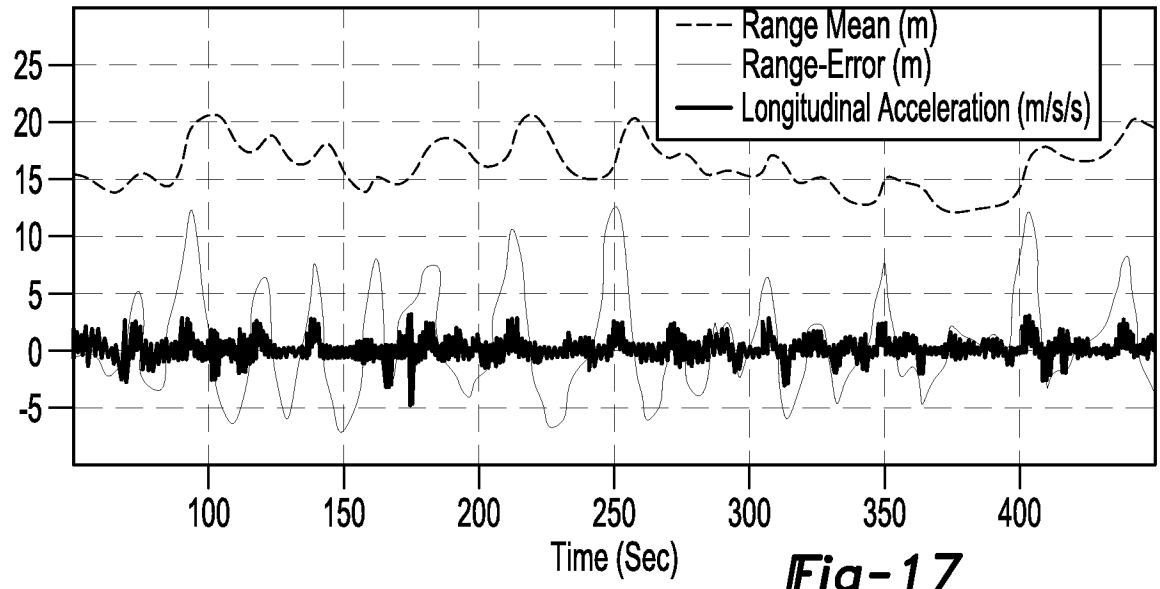


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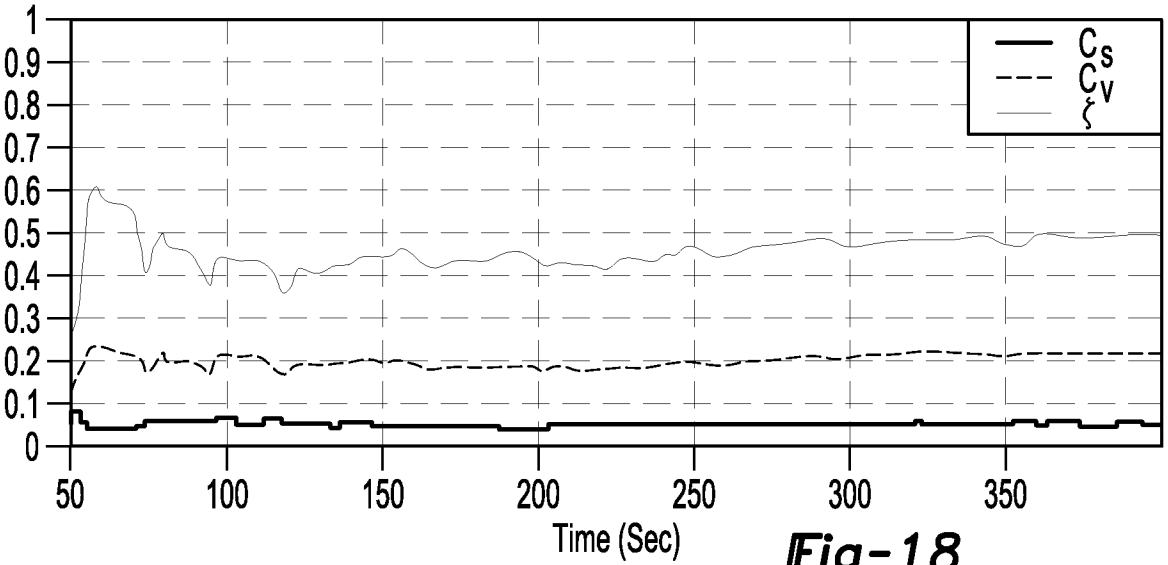


Fig-18

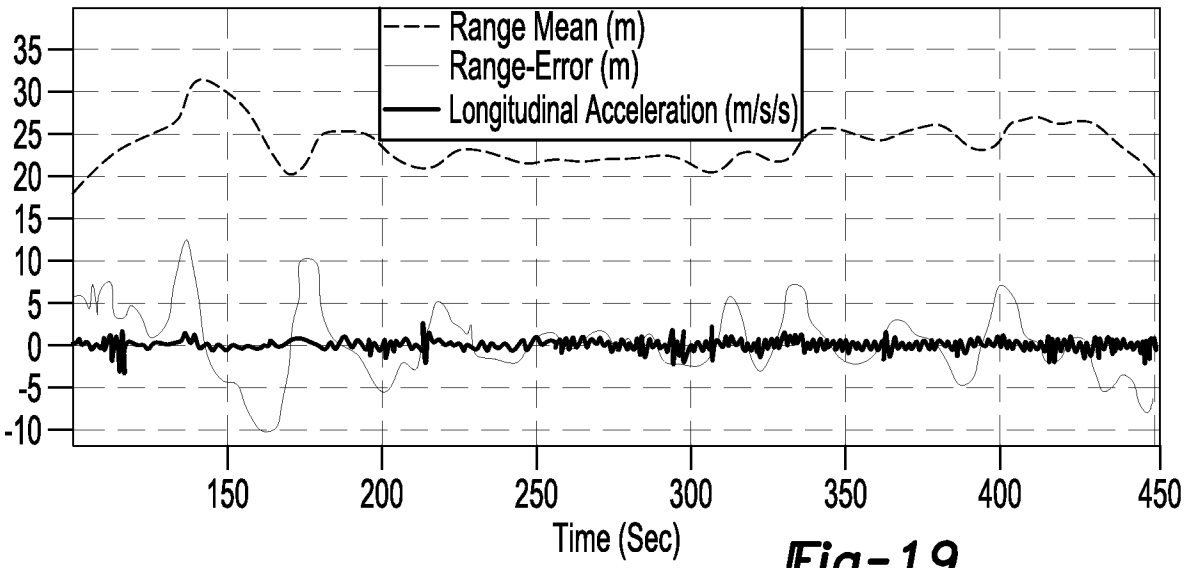


Fig-19

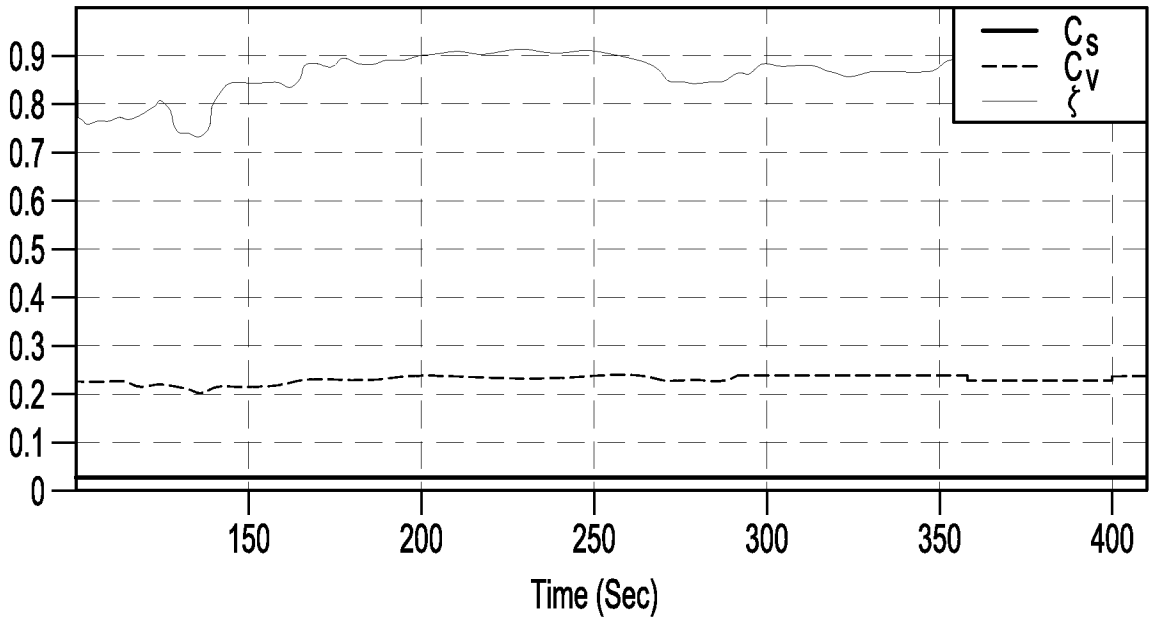

0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
150
200
250
300
350
400
Time (Sec)
Cs
Cv
ζ

Fig-20

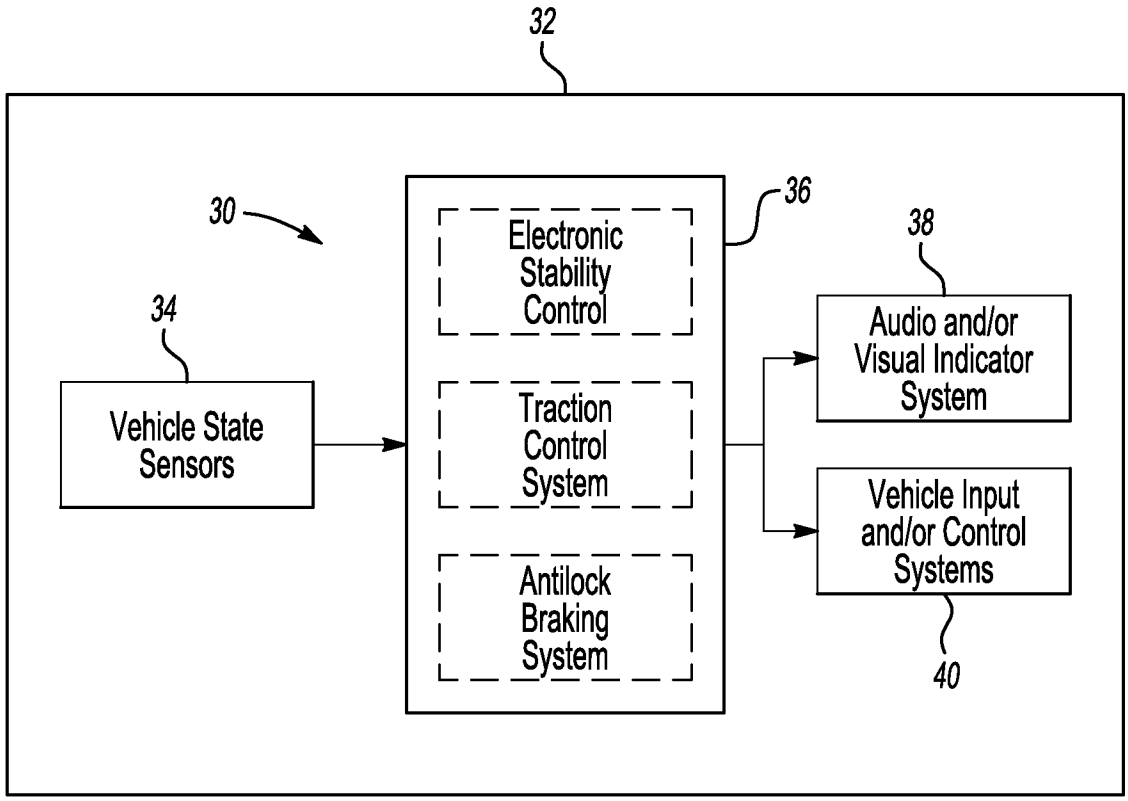

32
30
34
Vehicle State Sensors
Electronic Stability Control
Traction Control System
Antilock Braking System
36
38
Audio and/or Visual Indicator System
Vehicle Input and/or Control Systems
40

Fig-21

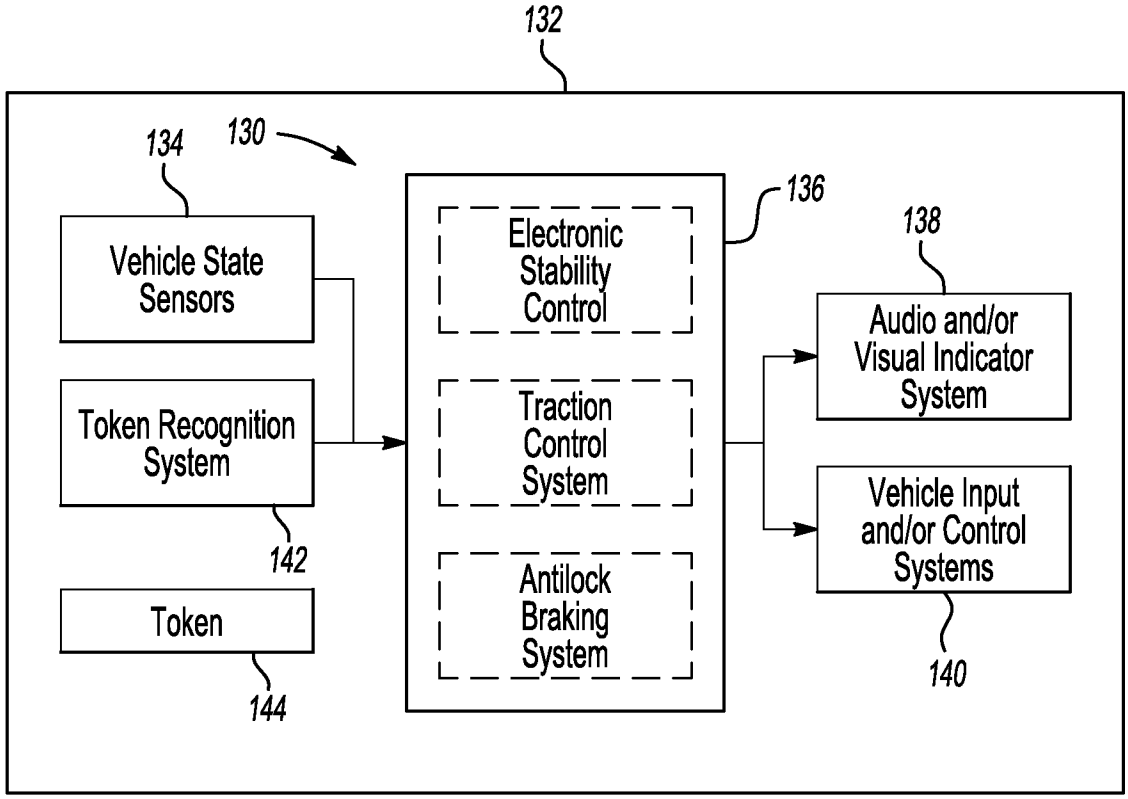

132
134
130
Vehicle State Sensors
Token Recognition System
142
Token
144
136
Electronic Stability Control
Traction Control System
Antilock Braking System
138
Audio and/or Visual Indicator System
Vehicle Input and/or Control Systems
140

Fig-22

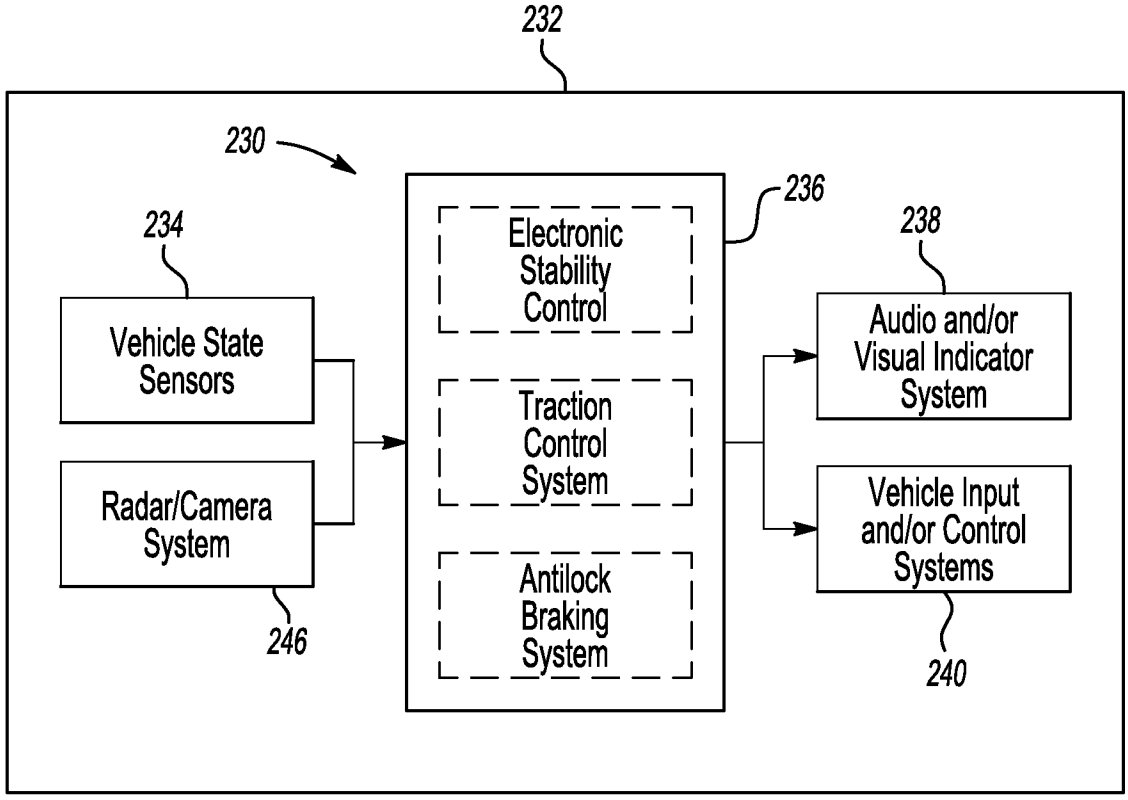

232
230
234
Vehicle State Sensors
Radar/Camera System
246
236
Electronic Stability Control
Traction Control System
Antilock Braking System
238
Audio and/or Visual Indicator System
Vehicle Input and/or Control Systems
240

Fig-23

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2009/062698

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B60K 28/16 (2009.01)
USPC - 701/48
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - B60K 28/16 (2009.01)
USPC - 701/48

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/0147277 A1 (LU et al) 19 June 2008 (19.06.2008) entire document	6, 14-19
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Y		1-5, 7-13
Y	US 6,695,294 B2 (MILLER et al) 24 February 2004 (24.02.2004) entire document	1-5, 7-10
Y	EP 1695859 A1 (MICHI et al) 30 August 2006 (30.08.2006) entire document	2, 3, 11, 12
Y	US 2004/0102887 A1 (LIN et al) 27 May 2004 (27.05.2004) entire document	5, 10
Y	US 2002/0161501 A1 (DULIN et al) 31 October 2002 (31.10.2002) entire document	13

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 December 2009	04 JAN 2010

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)