Paper Number

Study on Driver's Car Following Abilities based on an Active Haptic Support Function

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ABSTRACT

A research prototype system using novel graded haptic feedback to augment perception and control for car following applications is introduced and results from a field test evaluation are reported. The support system applies an active deceleration and gas-pedal push-back force whose magnitudes depend on the degree to which an undesirable region in a perceptual control space is penetrated. Because the support system essentially extends the driver's: i) perception (through force feedback on the gas pedal), ii) processing (information provided earlier and more saliently), and iii) control abilities (through superposition decelerations by the system), the system can be viewed an extension of the driver as a controller. Therefore, changes in car following behavior with and without support system are quantified by identifying the coefficients of a simple practical car following model of the driver alone versus the driver plus support system. The results clearly show that drivers who naturally follow closely, and thus operate frequently in the support system's active support domain, effectively have a higher control bandwidth with the system which means that they are able to more rapidly and accurately respond to changes in the gap to the lead vehicle. These drivers exhibited an improvement of car following performance (i.e. less variability in gap) as well as reported a reduction in workload. The support system effectively reduced the frequency with which drivers experienced close following and rapid gap closure situations. The supported driver is essentially more vigilant to gap changes while following at a greater time-headway without an increase in workload.

INTRODUCTION

Drivers are constrained in their car following performance by limitations in: i) detection, ii) situation assessment, and iii) control of gap changes. These limitations are exacerbated by road complexity, traffic complexity, in-vehicle task activity, and age. If drivers' ability could be augmented to overcome these limitations, car following performance would improve, and workload would reduce. Most existing driver support systems have not simultaneously addressed alerting the driver, situation assessment, and control . Rather, they generally support only detection (i.e. CAS) or part control (i.e. ACC). Moreover, previous systems have relied on traditional feedback mechanisms based on binary warnings.

To simultaneously support the driver along the three aforementioned dimensions of the car following task, a haptic gas pedal was developed whose push back force changes as a function of gap dynamics. This system supports detection (i.e. feel pedal force build up), assessment (i.e. strong push-back force or rapidly changing force indicates a more critical situation than a weak push-back force or a slowly changing force) , and limited control (i.e. the force pushes the gas pedal up unless the driver's leg is very stiff or the driver counter acts). This system is very effective in situations where only engine braking is sufficient for adequate gap maintenance.

Recognizing that the transition time from gas to brake pedal is a large factor in the driver's overall response time, a vehicle control component was added to the active haptic pedal that engages limited vehicle deceleration when the situation calls for active control, thus further aiding the driver in controlling the situation. The addition of an active deceleration component extends the system functionality to situations where the lead vehicle speed fluctuates such that limited hard braking is required for adequate gap maintenance.

The augmented driving ecology presented by the proposed haptic support system offers drivers more flexibility to manage the gap in a manner that is consistent with their multi-facetted situated goals, needs, biases, and skills.

AUGMENTED DRIVING ECOLOGY

Because driving is primarily a visual task, drivers are severely limited in their ability to flexibly manage their attention resources to satisfy the demands of the driving multitask (i.e. driving itself is a multi task that results in intermittent visual sampling of the forward driving scene). To support drivers better, support systems should augment the driving ecology by continuously informing the driver about the state of the vehicle relative to its relevant local surroundings (i.e. constraints) by using non-visual cues. These cues should be presented in close harmony with the existing visual cues to avoid that they significantly increase workload. This is supported by the fact that drivers are currently not confused by the multi-modal array of signals that they receive from the vehicle and its surroundings. The goal is simply to enrich this existing suite of signals and extend it to other perceptual modalities to facilitate effective, and efficient performance and safety management.

HAPTIC PEDAL AS AUGMENTED DRVING ECOLOGY

Nissan's research adopts a perspective thatgraded warnings and continuous non-visual ecologically inspired information and control channels. The proposed system is a haptic pedal whose push-back force is a function of the static and dynamic state of the gap to a lead vehicle. This results in a situation where the driver can feel how critical the longitudinal situation is when his eyes are directed away from the forward driving scene.

This continuous feedback haptic pedal has a number of benefits over the traditional binary warning systems:

- ✓ The origin of the threat is immediately obvious to the driver because the signal is communicated through the control channel (i.e. the gas pedal). In general, traditionally warnings are auditory and do not have any directional characteristics or an ecologically inspired sound such screeching tires. The paradox of binary warnings lies in the fact that a binary warning needs to be issued early enough for a driver to assess the source of the warning, assess the situation, and issue a response. However, if the driver is paying attention and aware of the situation, that warning will sound too early. If on the other hand, the warning would be issued when the driver would normally act to the situation, then the warning would be too late if the driver is not paying attention. This limitation is eliminated with an information channel that continually informs about the criticality of the situation in a non-intrusive manner.
- ✓ The criticality is immediately clear through the magnitude of the force as well as the rate of change in the force. For example, the driver can distinguish between a short slowly decreasing THW and a long rapidly reducing time headway[1] (THW). This enables the driver to decide to temporarily not react to the information or press the brake very rapidly depending on the experienced change in pedal force. Further advantage of the pedal force feed back is the information it provides is identical in nature to the visual information that driver naturally perceive about the state of the gap to a lead vehicle. The pedal force enables the driver to adapt the level of acceptable force and force rate (i.e. THW plus time to collision[2] (TTC) or range and range rate) to the context and situation at hand. In other words, the driver establishes his own acceptance levels on the pedal forces just as he does on the corresponding visual cues (i.e. adopt a situated satisficing interpretation of the state of relative vehicle state).
- ✓ The action required to maintain the safety margin is directly communicated. A rapid increase in pedal force communicates the need for an immediate brake depression whereas a slowly increasing force communicates the need to release the gas pedal. Such a distinction is not possible with a single binary warning system unless different tones are used for different actions, but that would only add to the driver's confusion if the tones are not highly ecological. The haptic pedal provides a single interface that communicates to the driver at multiple levels of information processing according to their own situated goals and needs.

The system aids the driver by effectively augmenting the driving ecology from a primarily visual ecology into the domain of haptic perception thereby giving the driver more flexibility to maintain awareness of the situation and manage safety.

AUTOMATION AS AUGMENTED VEHICLE DYNAMICS

Drivers are limited in their ability to quickly depress the brake and therefore in their ability to quickly achieve the desired deceleration rate. Under normal driving conditions, drivers have sufficient preview and can anticipate far enough in advance that these delay-type limitations can be overcome by initiating a control signal earlier. Unfortunately, in critical situations, almost by definition, preview and anticipation are not available or failed and an instantaneous response is needed.

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[1] Time headway is the time it takes the following vehicle to reach the current location of the lead vehicle assuming no change in the current speed. Mathematically it is the distance to the lead vehicle divided by the following vehicle's speed.

[2] Time to collision is the time it takes the following vehicle to collide with the lead vehicle assuming no change in the current speed of both vehicles. Mathematically it is the distance to the lead vehicle divided by the relative speed between the two vehicles.

Just as the haptic pedal aids drivers in overcoming their limitation to remain continually aware of the situation due to necessary visual attention diversions (e.g. assess situation for a lane change), an active deceleration is used that aids drivers in overcoming their limitation to react quickly especially when hard braking is needed.

For both support components, the driver can fully or partly null the effect. The driver can fully null the effect of the force on the pedal by delivering a counter force, and the driver can null the effect of active deceleration by depressing the gas pedal. In other words, the driver is fully able to manage vehicle speed and THW albeit with more work when the system feels the currently risk potential should not go unnoticed or ignored. In case of the active deceleration, the maximum deceleration authority is similar to that of Adaptive Cruise Control (ACC) system . Given that a vehicle cannot accelerate at maximum rate especially at high speed, the system deceleration cannot be nulled fully in the most critical situations. However, if a maximum deceleration is issued by the system, the chance is very small that the driver would not wish to decelerate. A few exceptions may be when the driver is aggressively overtaking or when the driver approaches a slow vehicle that is turning out of the lane. In both cases, the support provided by the system is biased to the safe side and guards drivers against wrong assumptions about other road users' intentions and actions

Traditionally the driver only controlled the state of the vehicle; the gas pedal interpretation depended only on the forces directly acting on the vehicle. If the vehicle drove uphill, the gas pedal needed to be depressed more to achieve a given speed compared to a flat road. The Nissan prototype system augments the interpretation of the gas pedal by artificially creating forces on the vehicle that depend on the state of the vehicle relative to that of a lead vehicle. As the gap decreases, a stronger force pushes the car back which is communicated to the driver through pedal forces and an active deceleration (the pedal force and the deceleration are both functions of THW and TTC). This simple virtual force metaphor aids drivers in quickly gaining an intuitive understanding of the situated system functioning.

PROPOSED ACTIVE HAPTIC SUPPORT

So far, the system has been described from the driver's perspective. In this section, a system based description is provided. The support system researched is an active graded gap maintenance support system that consists of two complementary components:

- ✓ Accelerator pedal reaction force added to the normal the gas pedal reaction force. Additive force levels correspond to proximity level to the lead vehicle whose push back force increases as THW and/or TTC decrease (i.e. close or closing situations) and
- ✓ A driving and braking force control whose deceleration increases also as THW and/or TTC decrease.

The operational domain in the perceptual state space spanned by THW and InvTTC got the pedal force is greater than for the active deceleration. Drivers generally feel the pedal force build up before the vehicle engages active deceleration. The pedal pushback force and the active deceleration are both limited in magnitude.

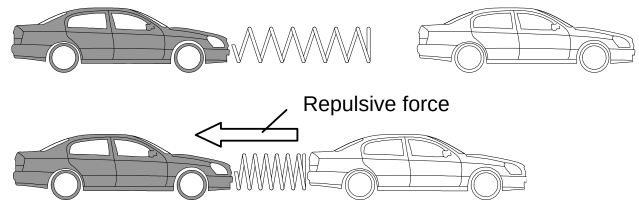


Figure 1. Concept of the prototype driver supportsystem. A repulsive force acts on the vehicle and gas pedal. The repulsive force only acts within a certain close proximity and closing domain that is defined by THW and TTC. Two different springs are used: one for generating the force that influences active vehicle deceleration and a longer one that influences the gas pedal push back force.

To quantify the proximity level to the lead vehicle, a repulsive force concept was introduced. As shown in Figure 1, an imaginary spring is installed in the front of the vehicle that generates a repulsive force when it touches the lead vehicle and increases as the vehicle approaches the lead vehicle more as shown in Figure 1. The degree to which short THWs and short TTCs are experienced influences the magnitude of the repulsive force. Accelerator pedal force and active deceleration are determined in the way that for a larger repulsive force, stronger pedal force and deceleration would be produced.

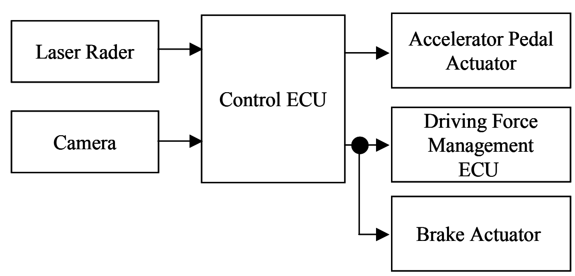


Figure 2. System Configuration of the prototype graded active haptic car following support system.

This concept was used in the proposed system and implemented in an instrumented prototype vehicle [1]. The system consists of a laser-radar, a camera, a brake actuator and an accelerator pedal actuator. The system configuration is indicated in Figure 2 and the various components of the prototype vehicle are shown in Figure 3.

EXPECTED SYSTEM BENEFITS

The perceptual and control augmentation provided by the driver support system is expected to support the driver in his detection, criticality assessment, and response mediation. The virtual repulsive force based support system aids the driver in three main ways:

- ✓ It informs the driver that the gap is small or decreasing through the increase in gap pedal pushback force; this gives the driver an early graded warning to which they can either further release the gas pedal or press the brake when the pedal force increases rapidly which is indicative of a fast closing gap.
- ✓ It pushes the driver's foot up or equivalently it reduces the gas pedal depression when the gap is small or closing; this slows the vehicle a little bit thereby giving the driver a little more time to manage the gap before greater criticality levels develop.
- ✓ It actively decelerates the vehicle to open a small or closing gap through engine or hard braking; this slows the vehicle substantially giving the driver even more time to depress the brake and in some cases eliminates the need to press the brake (Figure 7).

Because the driver can push through the pedal force, the driver can override the system and effectively null the system effect. The same is true for the active deceleration to a certain degree. The system takes the torque demand of the driver (i.e. the throttle opening) and subtracts from that the active deceleration demand of the system. Given that the maximum active deceleration demand of the system is greater than the maximum acceleration demand of the driver, the system would provide a directionally appropriate response in critical situations and the net effect will be that the system decelerates even if the driver fully depresses the gas pedal.

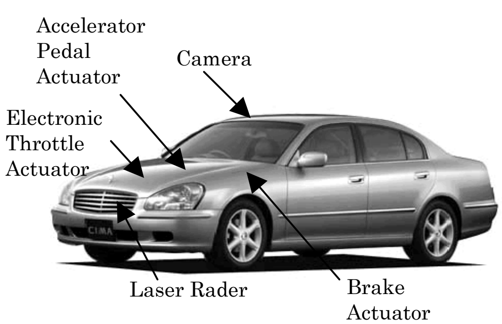


Figure 3. System components of the Q45 Infiniti prototype vehicle.

The cooperative shared-control nature of the system enables the driver to use the system across a range of situations because the system enables the driver to flexibly interpret the meaning of the pedal force and vehicle deceleration and enables the driver to over ride the system actions to a large degree.

The proposed system is characterized as a cooperative system that augments driver's perception of the vehicle's dynamic state relative to local constraints (e.g. gap to lead vehicle) and that augments the experienced vehicle dynamics by virtually coupling the vehicle to the local constraints (e.g. gap lead vehicle).

FIELD EXPERIMENT

In order to assess the performance of the system in the real world, a field test was conducted in which 15 subjects drove a prototype vehicle for over an hour of highway driving on the freeways around Minneapolis and St Paul, Minnesota. Subjects were instructed to drive as they normally would.

EXPERIMENTAL DRIVE ROUTE

Two separated highway routes with different characterstics were chosen so that assessment could cover a wide range of driving environments. Both routes started from University of Minnesota and ended back there. Each subject experienced both routes with and without the system. Basic traits of the routes are described below.

- ✓ Route 1: This 22 mile route had moderate vehicle volume. Drivers were involved in car following situations most of the time and were able to maintain speeds from 55 to 65 mph which are up to the posted speed limit. Average time to traverse the routes was 35 minutes.
- ✓ Route 2: Drivers were asked to run this 15 mile route twice consecutively. Traffic was heavy. Total time to traverse route 2 twice was about 30min.

The two routes assured that drivers experience a wide range of lead vehicle speed fluctuations (see Figure 9 for a distribution of lead vehicle deceleration rates and durations).

TEST VEHICLE

Above mentioned prototype vehicle with the driver support system shown in Figure 3 was used in the experiment. Driver support function could easily be activated and deactivated by the experimenter. The vehicle behaves as a normal vehicle when the support system is turned off. Data recording system was installed in the vehicle.

SUBJECTS

Participants were recruited via a classified advertisement that appeared in a major local newspaper. Nissan and Infiniti owners were prioritized because the possible bias and longer familiarization time associated with learning to drive a high-end vehicle is eliminated. Two age groups were chosen to analyze age effect (not reported in this paper – results collapsed across age). Seven younger drivers (33.43 years old in average, 6 males and 1 female) and eight older drivers (68.25 years old in average, 6 males and 2 females) participated in the study.

PROCEDURES

Each subject drove the same Q45 with and without support system activated. Before starting the experimental drive, two practice drives were provided to the participants; the first to familiarize them with the Infiniti Q45, the second to actively learn how the system works. Documentation on system functions was provided prior to the second drive and they had a chance to test functions during their second drive and could ask questions to the experimenter in the passenger seat.

The experimental drive consisted of two driving sessions per route (one with and one without support system enabled). All participants experienced the route 1 first and the route 2 second. Order of route was fixed to have participants drive route 2 at a certain time of the day to ensure that lots of vehicles converged into the area, but did yet result in stop and go conditions. Presentation of system condition in the same session was randomized to consider order effect. Drivers were instructed to drive as they would normally in the same circumstances using their own personal vehicle. Participants were paid USD150 for their participation.

FIELD DATA PREPARATION FOR ANALYSIS

The time series data from the instrumented vehicle was filtered, screened, and prepared for further driver-model based analysis. The original sampling interval was 10ms. Only those segments of data that satisfied the following criteria were used in the analysis:

- ✓ Keep all data portions where the lead vehicle accelerates from a speed greater than 12m/s to one greater than 20m/s[3].
- ✓ Keep all data portions where the lead vehicle decelerates from a speed greater than 20m/s to one greater than 12m/s.
- ✓ Eliminate those portions where the lead vehicle speed increases from a speed less than 12m/s to one greater than 20m/s. This removes all portions where the vehicles speed up from a traffic jam or on-ramp.
- ✓ Eliminate those portions where the lead vehicle speed decreases from a speed greater than 20m/s to one less than 12m/s. This removes all long decelerations to a traffic jam or an exit.
- ✓ More than 20s of continuous following of the same vehicle (i.e. no gaps or breaks in range data; defined as range jumps greater than 6m or time gaps greater than 50ms.).
- ✓ Median range to lead vehicle of a valid segment has to be between 0 and 60m or about a THW between 0 and 3s. At longer THWs it is arguable that drivers are not in car following mode but in speed regulation mode for a large portion of the segment particularly given the fact that the median THW of the subjects is between 1s and 1.5s and the maximum speed about 30m/s.

Enforcement of these criteria assured that only clean car-following segments were kept for further analysis (and thus would not negatively affect the model identification). Given the gap controllability focus of the paper, the subsequent car following period exceeded 20s as well as cut-ins and lane changes were extracted.

The first two criteria assured that all segments on surface roads to and from the freeways were automatically removed.

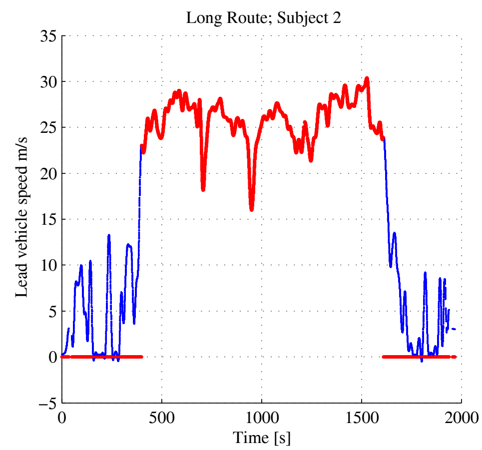


Figure 4. Example of the “normal” car following data selected for further analysis (solid line). The periods of slow speeds as well as accelerations from slow speed and decelerations to slow speed are excluded from the analysis.

The relative velocity data was derived from the range data using a non-causal filter to assure that the relative velocity and range are not out of phase by more than the required 90 degrees. This guarantees more accurate analysis than with the relative velocity data from the radar system directly since that is by definition lagging the distance measurements (note for real time control a non-causal filter is not feasible but for post-drive analysis it improves analysis).

The final valid time series were sampled down to 10Hz from 100Hz.

These screening criteria yielded on average 18 valid segments per subject per condition (i.e. baseline and supported) at an average duration of about 38s (minimum is 20s and maximum is 150s). The average total amount of valid data per subject is on average 1954s or about 32min.

DRIVER BEHAVIOR ASSESSMENT

The driver support system augments driver’s perception and control. To determine the degree to which gap maintenance control is affected by the support system, a model theoretic approach is advocated as one of the perspectives for interpreting the data. The idea is that a

[3] In order to determine the peaks and valleys in the speed data time series, it was forward and backward filtered, to avoid a filter induced lag) with a 5th order Butterworth filter with a 0.05Hz cutoff frequency. The raw speed data was used for all subsequent analysis.

joint-system of driver plus support system can be characterized by a simply controller (i.e. dynamic model). This model is identified per support condition (baseline and supported) for each subject separately as well as across all subjects. The observed changes in model coefficients offer an integrated view on how and why the system influenced overall control.

Driver behavior was assessed in a number of complementary ways:

- Changes in THW and TTC distributions showing the effect of the system in terms of safety and performance.
- Changes in model coefficients showing how these changes were produced (e.g. what changed in terms of control from driver alone to supported driver).
- Time series responses to gain deeper insight into the meaning of the observed changes in model coefficients.

These complementary perspectives offer insight into the manner in which the support system altered the way in which the driver plus system managed the gap to the lead vehicle compared to driver alone. It shows how the driver plus support system behaves different as a controller than the driver alone.

Good performance is defined as the ability to avoid: i) small gaps, ii) rapidly closing gaps, and especially iii) small gaps that are rapidly closing. From this definition it is clear that simply looking at changes in the THW or TTC distribution is not sufficient because short THWs are more acceptable when the gap is opening than when it is closing. In Figures 12 and 13 we will see that the support system effectively removes short THWs with negative TTCs (i.e. closing gaps) even though the number of very short THWs does not decrease as seen in Figure 5.

In many analyses inverse TTC (InvTTC) is used to avoid dealing with infinity when the gap is non-changing.

THW AND TTC VARIABILITY ANALYSIS

Arguably, a good controller is one that is capable of maintaining a THW that remains close to a target. This is why our basic analysis focuses on changes in the THW and TTC distributions.

<u>THW and TTC variability results</u>

The cumulative distributions of THW and InvTTC observed for the baseline (solid) and support (dashed) conditions are shown in Figure 8. A negative InvTTC or TTC signifies a closing gap. The changes between baseline and supported at different percentiles is shown in Figure 5. It shows that:

- ✓ The frequency of occurrence of short THWs observed during unsupported baseline driving decreases significantly and for some subjects substantially when they drive under support of the system. This means that the support system effectively reduces the frequency with which drivers encounter very short THWs during normal car following situations. For all but one subject a comparison of the 5 and 50-percentile THWs between baseline and supported driving shows an increase.
- ✓ Interestingly the 0.5-percentile THW decreases for about one third of the subjects. As will be shown in the 2D CDFs in Figures 12 and 13 a shift from closing to opening short THWs is observed with the system. This means that the frequency of very short THWs does not decrease but that the number of short THWs that are shrinking does decrease; they are replaced with short THWs that are increasing (i.e. from negative to positive Inv TTC in Figures 12 and 13).
- ✓ The frequency of occurrence of short negative TTCs or equivalently large negative IncTTCs (i.e. closing situations) during unsupported baseline driving decrease significantly and for some subjects substantially when the support system is engaged. This means that the support system is very effective at avoiding short negative TTCs during normal car following situations. For all but a couple subjects, the 0.5, 5, and 50-percentiles show longer TTCs during supported driving compared to unsupported driving.

These results clearly indicate that the system has a very positive effect on drivers' ability to maintain the gap to the lead vehicle more frequently within more acceptable bounds.

Because both CDFs are steeper for the supported case, it suggests that the system enables the driver to stay closer to a fixed target THW. This is also confirmed in the 2D distributions of Figures 12 and 13 because the distributions are more tightly clustered around the model of the distribution (i.e. the target THW).

As already alluded to, the problem with these assessments along a single THW or InvTTC axis is that they do not show whether the occurrence of short closing TTCs (i.e. large negative Inv TTC) shifts to longer THWs. That this is indeed the case is shown in the 2D frequency plots in Figures 12 and 13. Before these 2D distributions are discussed, the model based analysis is introduced and results discussed.

MODEL BASED ANALYSIS

Given the focus on car following that excludes very slow speeds including accelerations from slow speeds and decelerations to slow speed, the effect of the support system will be discussed in the context of how driver plus system as a single vehicle controller differs from the driver alone as a vehicle controller.

The driver and system are simply modeled as follows

$$a(n) = C_{THW}\left(THW^* - THW(n-1)\right) + C_{TTC}v_r(n-1)$$

Which has three unknowns tan that need to be identified namely: the desired THW (THW^*), the gain on deviations from the desired THW (C_{THW}) and the gain on deviations from stable gap or a non-zero TTC (C_{TTC}). The current time step is denoted by (n). The sampling interval was set to 100ms (it was sub-sampled from original 10ms). $v_r(n-1) = v_l(n-1) - v_h(n-1)$ is the relative velocity at time step n-1 defined as the difference between lead and host vehicle speed.

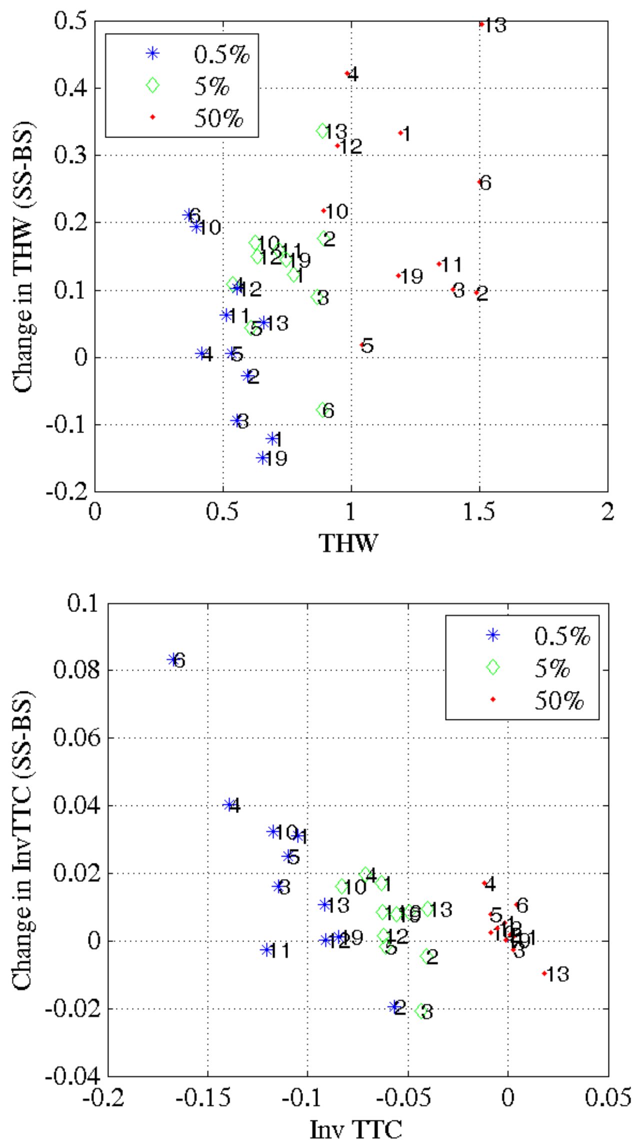
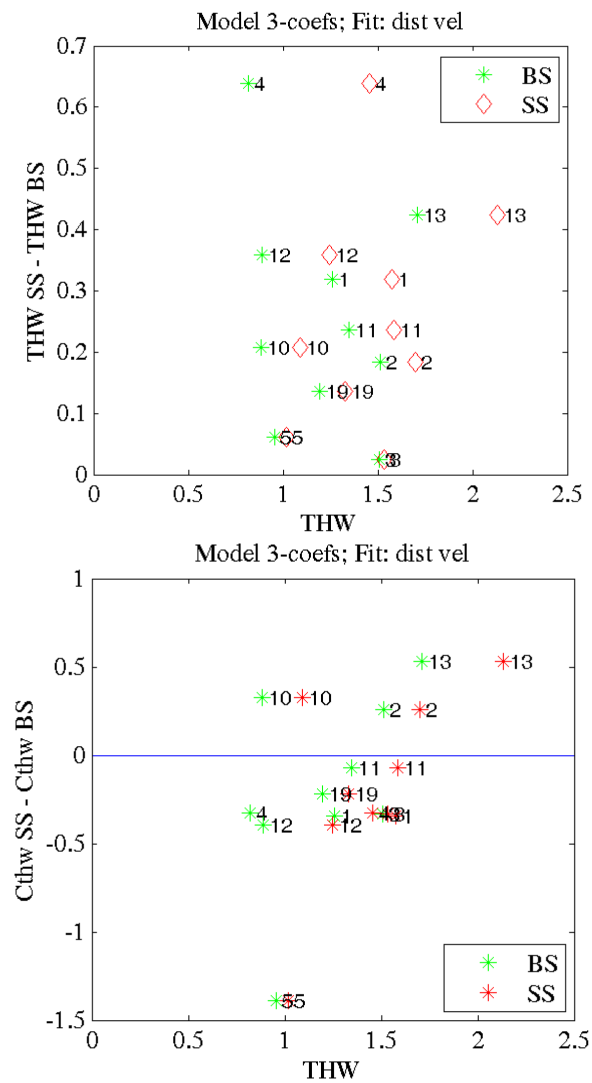


Figure 5. Top panel shows the changes in 0.5%, 5%, and 50% for THW between support system (SS) and baseline. The bottom panel shows the same for InvTTC.

A positive THW error means that the gap is too small and a deceleration is needed. This means that C_{THW} is likely to be negative. The relative velocity is negative when closing and thus a deceleration is needed. This means that C_{TTC} is most likely positive. Instead of v_r it is also arguable that Inv TTC should be used. However, when this was tried, the model fit was not as good. The reason for this is beyond the scope of this paper. Here it is only important to note that the model captures the driver as well as driver plus system as a controller so that a meaningful and practical comparison can be made. The goal here is not to establish a perceptually accurate car following model of the driver (see [2,3,4,5] for details on driver models of car following). Below the subscript TTC and relvel are used interchangeably both referring to the rate at which the gap opens or closes.



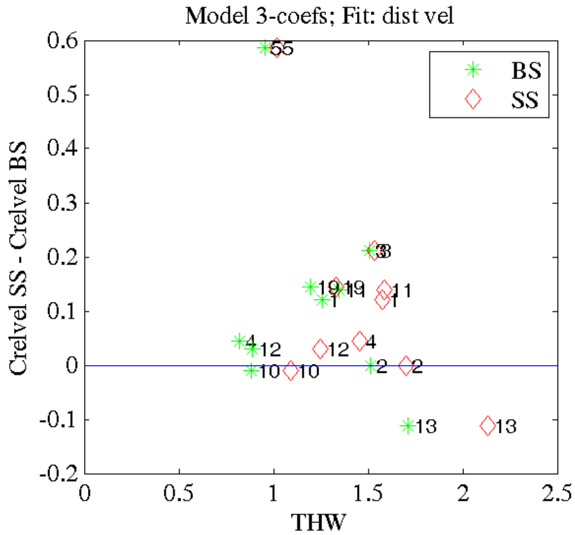


Figure 6. Changes in model coefficients for each subject. Top panel shows change in target THW as a function of THW; it shows it against BS THW (asterix) and against SS THW (diamond), the middle panel the change in Cthw and the bottom panel the change in Crelvel.

A model is identified for each driver for each condition (i.e. baseline and supported). This means that 3 model coefficients are obtained for each subject under each support condition.

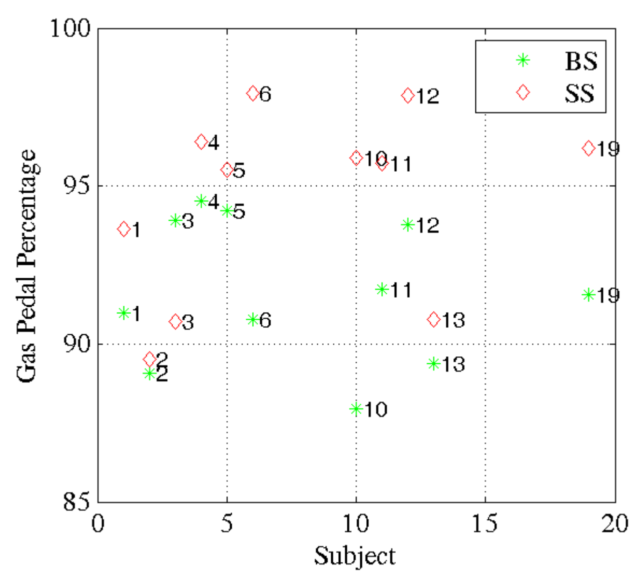
The model is identified using a time based identification technique where the fit across all valid data segments is minimized (see [2,4] for details). The fit is a combination of model predicted distance to host vehicle and host velocity matching to observed data. The model is initialized with observations for each data segment before it is run with the currently best guess model coefficients for the duration of the data segment in question. The fit is computed for each data segment separately and added together weighted by duration of the data segment. A gradient search for the optimal coefficients is used based on a starting guess of all coefficients at zero.

<u>Model results</u>

The results of comparing the supported and unsupported model coefficients are fourfold (shown in Figure 6):

- ✓ The target THW increases for all subjects by about 300ms on average under the supported condition. This is consistent with the changes in THW CDFs shown in Figure 8.
- ✓ The gain on a THW error (i.e. C_{THW}) increases (i.e. becomes more negative) with support system except for 3 subjects, namely 2, 10 and 13. Subjects 2 and 13 operated at long THWs and thus operated primarily outside the THW,TTC support domain and thus their gain is less affected by system influence. Given that they do follow at a greater distance with the system and the fact that their relative velocity gain (lower panel in Figure 6) is also unchanged or decreased is consistent with the fact that effectively unsupported drivers are less vigilant to gap changes at longer THWs [4]. Subject 10 is an outlier because he experienced the greatest lead vehicle deceleration activity during baseline driving and less demanding lead vehicle speed fluctuations during supported driving. This means that subjects 10 had to be most vigilant during baseline and thus operated at higher gains (i.e. subject 10- reduced his negative C_{THW} in magnitude during supported driving because the driving conditions were less demanding – the driver may not have expected large lead vehicle decelerations).
- ✓ The gain on THW deviations (middle panel) decreases most at shorter target THWS. All points fall on an up-sloping line expect outlier subject 10. This is a general trend shown in unsupported driver [2,4]. The difference is that supported drivers operate with a higher gain on relative velocity (bottom panel) which is opposite of what is seen in un-supported driving. This suggests that the support system results in a higher bandwidth control because the driver plus support system responds stronger to relative velocity changes suggesting rather than wait for THW to change substantially.
- ✓ The gain on RelVel error (i.e. C_{TTC}) increases (i.e. becomes more positive) with support system except for subjects 2, 13, and 10 again. The reason for their discrepant effects is the same as discussed under the previous bullet.

These results clearly suggest that the driver-system controller is more vigilant than the driver alone because it responds stronger and faster to gap changes and essentially changes from a THW to a relative velocity controller which has a much lower lag as will be shown in the time responses in Figures 10 and 11.



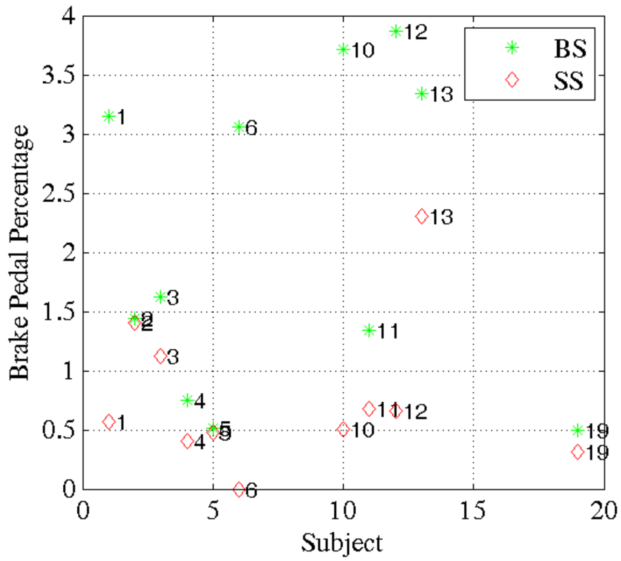


Figure 7. Changes in gas (top) and brake (bottom) pedal activity between baseline (asterix) and support system (diamond) condition.

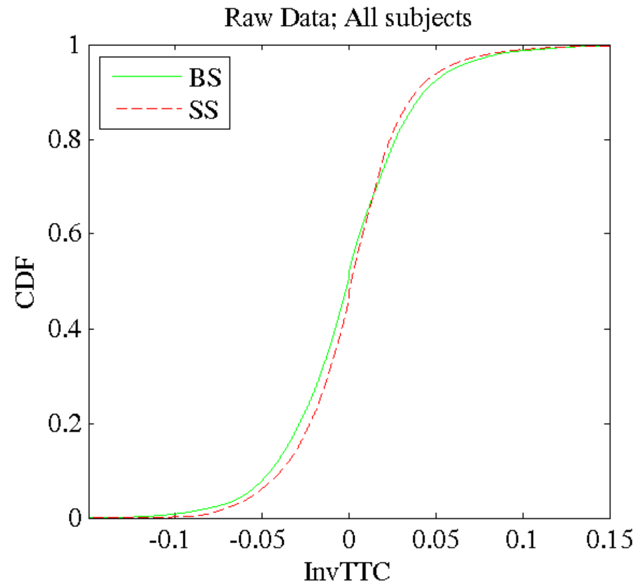
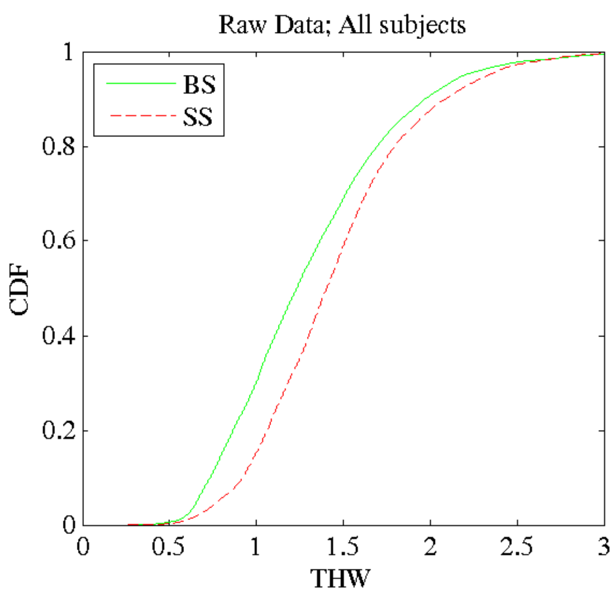


Figure 8. Top panel shows general increase in THW as well as tightening with support system. Bottom panel shows decrease in rapidly closing and opening gaps as well as a tightening of the entire InvTTC distribution (and thus control).

Because the system pushes the pedal (and the driver's foot moves immediately whether the driver is aware of it or not) and engages active deceleration, the system lag is less than that of an unsupported driver. Thus the combination of driver plus system effectively decreases the driver's lag or delay. Because the system actively pushes the foot up and actively decelerates, the driver plus system gain is greater than that of the unsupported driver. The total effect of these mechanisms is that the driver plus system controls at a higher bandwidth than an unsupported driver (i.e. higher gain lower phase at given input frequency).



Because the driver plus system responds faster and stronger than the unsupported driver, gap decreases are responded to earlier and stronger and thus do not develop to the same level of criticality as what they would for the unsupported driver. This has several secondary benefits. Because the response is earlier and stronger, the driver does not need to press the brake as frequently and thus keeps his foot on the gas pedal more frequently (Figure 7). This assures that the haptic communication channel is active longer than expected purely based on baseline gas pedal depression statistics. Furthermore, because the applied decelerations are lower with system than without the system, this may also be beneficial for following vehicles in that the system may be reducing the number and strength of deceleration shockwaves that it generates in its wake.

Two additional effects on the THW and TTC distributions are important to bring forth based on the THW and InvTTC cumulative distribution functions in Figure 8:

- ✓ The frequency of large gap opening rates is significantly reduced by the support system. This is consistent with the reduction in large closing rates. It suggests that drivers do not overreact as much with the support system as without. Their phase trajectory in the THW, InvTTC phase plane is tighter around the target THW with the support system (clearly seen in denser concentration around target THW in Figures 12 and 13 with support versus without support). This also makes them less vulnerable for secondary lead vehicle decelerations (i.e. a change to a stronger deceleration).
- ✓ This is also consistent with the increased gain on RelVel which should reduce strong opening and closing situations.

This brings us to an interesting question, namely whether drivers naturally adopt a different gain for opening and closing. It should also be noted that the gains of the support system is primarily on closing. The reason we say primarily is that the push back pedal force decreases during opening thus aiding the driver to quickly and appropriately depress the gas pedal to settle in on the target THW. This effect will show up in a model as an increase in opening gain (confirmed below).

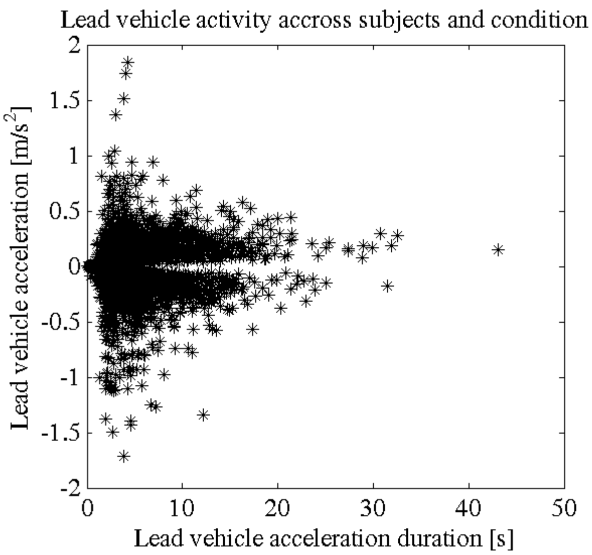


Figure 9. Distribution of lead vehicle acceleration and deceleration events across all subjects and both conditions (i.e. baseline and supported).

<u>Asymmetric control analysis and results</u>

To gain deeper insight into the possible asymmetry between responses to opening and closing gaps the model was expanded to include a different gain for opening and closing. The resulting model is:

$$
\begin{aligned}
a(n) = {} & C_{THW_{small}} \max\{0, THW^* - THW(n-1)\} + \\
& C_{THW_{large}} \min\{0, THW^* - THW(n-1)\} + \\
& C_{TTC_{opening}} \max\{0, v_r(n-1)\} + \\
& C_{TTC_{closing}} \min\{0, v_r(n-1)\}
\end{aligned}
$$

It turned out that the amount of data available per subject is not sufficient to identify the 5 model coefficients stably. Thus the model was identified per support condition on the combined datasets from all subjects. This lead to a baseline condition model and a support condition model.

The baseline model is:

$$
\begin{aligned}
a(n) = {} & -0.72 \max\{0, 1.02 - THW(n-1)\} - \\
& 0.15 \min\{0, 1.02 - THW(n-1)\} + \\
& 0.17 \max\{0, v_r(n-1)\} + \\
& 0.16 \min\{0, v_r(n-1)\}
\end{aligned}
$$

The supported model is:

$$
\begin{aligned}
a(n) = {} & -0.39 \max\{0, 1.37 - THW(n-1)\} - \\
& 1.04 \min\{0, 1.37 - THW(n-1)\} + \\
& 0.24 \max\{0, v_r(n-1)\} + \\
& 0.49 \min\{0, v_r(n-1)\}
\end{aligned}
$$

It is clear that the gains are not symmetrical for the baseline nor supported condition. It is also clear that the average gain corresponds relatively well with the gains obtained when the 3 coefficient model is identified across all subjects. The respective models are again identified across all subject data per condition:

Baseline:

$$a(n) = -0.33(1.23 - THW(n-1)) + 0.2 v_r(n-1)$$

Supported:

$$a(n) = -0.60(1.45 - THW(n-1)) + 0.3 v_r(n-1)$$

It is clear that the effects of increased target THW and increased gains also show up in the aggregate 3-coefficient model reflecting a more vigilant driver operating at a longer target THW. Normally drivers are less vigilant (lower gains) when they operate at a longer THW due to the inherent tradeoff between performance and workload in human operators [3].

In terms of the 5 coefficient model, the following effects of the support system on the driver as a controller are observed:

- ✓ The RelVel gain C_{TTC} on closing is much greater for the supported than the unsupported conditions clearly showing the benefit of the pedal force reducing pedal depression as well as the active deceleration.
- ✓ Even though it was argued that the pedal also increases gain and decreases lag during the process of closing the gap to the desired target THW, this only works when THW and TTC are in the domain where the active pedal operates because only in that domain do we have a relationship between changes in pedal force and resultant changes in pedal position through driver’s admittance. The operational domain of the support system is bounded by an upper THW of 1.4s, which means that a relatively short portion of desirable gap closing phase falls in the operational domain, hence the small

opening gains (note that the gains are most likely the average of a much higher gain when THW<1.4s and a lower gain when THW>1.4s.)

- ✓ The target THW is larger with the support system.
- ✓ Interestingly, in the baseline condition, the gain on a THW error is high for small gaps and low for large gaps whereas the supported condition shows the opposite. The most likely explanation for this high large-gap gain is that drivers adopt a THW that corresponds to a force that is natural for them. It may be that drivers simply depress the pedal and wait until the pedal force kicks in and settles them on a natural depression (may depend on foot weight and ankle angle). Furthermore, the fact that the gain on a small THW is smaller in the supported conditions may be attributed to the fact that short gaps generally are the result of a closing gap (except when a car cuts in at a very short range) and that the high RelVel gain is primarily responsible for causing the vehicle to decelerate.

It appears that the support system changes the controller from a primarily gap size controller (unsupported condition) to a primarily gap velocity size controller (supported condition). This is a more effective control strategy as it offers preview about what the gap will be some time in the near future and thus effectively applies gap size control on a gap predicted some time into the future. This suggests that the system complements the driver by augmenting its ability to perceive and respond to gap changes. Perception to detect small gap changes is difficult for humans but it is exactly the skill to detect small changes and respond to them before they escalate that keeps control effort low and performance high (i.e. ability to keep THW close to target).

The 5-coefficient model makes several predictions about the changes in THW and TTC distributions, which are all confirmed by the observations in Figures 5,8, 12.

1. The mean or median THW shifts to a higher value because the target THW increases with active support.
2. The THW and InvTTC distributions are tighter with support because of the higher gains and concomitantly smaller lags. This results in the observed decrease in frequency of occurrence of short THWs and TTCs.

The model provides an encapsulated causal understanding about the origin of the observed changes in THW and TTC (or InvTTC) distributions.

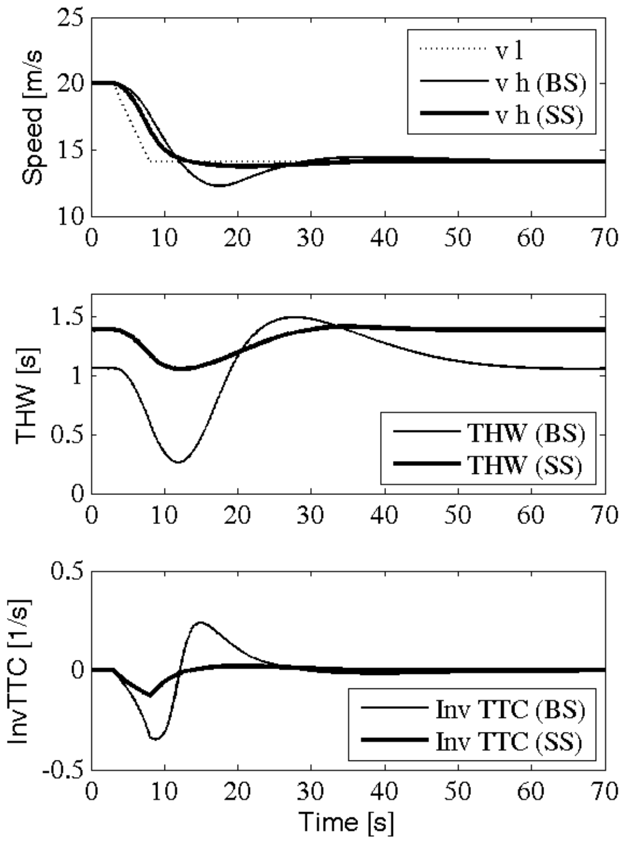


Figure 10. Response of the baseline and support 5-coefficient common model (i.e. one model representing all drivers) to a lead vehicle deceleration of 1.2 m/s^2 for a duration of 5s. The baseline model was initialized at its target THW and the support condition model was initialized at its target THW. Lead and host vehicles were both assumed to travel at 20m/s.

To gain insight into the effect of a longer target THW and larger gains on control, the response of the 5-coefficient baseline and support system models are shown in Figures 10 and 11. In order to determine a representative critical situation for simulation, the peaks in the lead vehicle velocity profiles were identified and the speed difference and time difference between consecutive velocity peaks collected and plotted in Figure 9. This provides a measure of the magnitude and duration of deceleration and acceleration of the lead vehicle.

Figure 9 shows that a representative critical situation is one where the lead vehicle decelerates for 5s at about $1.2 m/s^2$ which does require more than engine braking and will engage the active deceleration. Figure 10 shows the responses to such an event as generated by the baseline and support condition 5-coefs models.

It is very clear from this figure that the supported condition has a response with a smaller lag and very little overshoot . The minimum THW reached is greater for the supported condition and the rapid opening and closing situations are also non-existent in the supported case. Clearly the supported condition yields an efficient driver plus system controller. The time responses also show that the total time it takes to reach steady state again is much longer in baseline than in the supported condition which contributes to increased workload under unsupported conditions.

Figure 11 shows the response of the 5-coefficient models for the baseline and support system conditions to a sinusoidally fluctuating lead vehicle speed profile. The same criticality of the situation is used, namely 5s deceleration of about 1.2m/s^2.

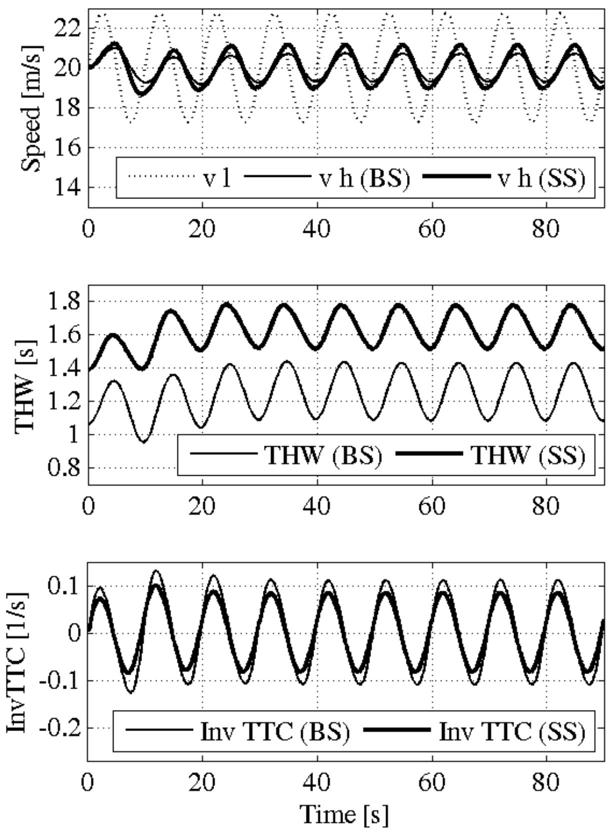


Figure 11. Time responses of the composite baseline (BS) and support system (SS) models. The lead vehicle speed profile follows a sinusoid with a frequency of 0.1Hz and an amplitude of 2.75m/s. The top panel shows the host vehicle's speed response, the middle panel the resulting THW fluctuations and the bottom panel the emergent InvTTC profile.

It is again clear from figure 11 that the driver plus support system (solid line SS condition) shows: i) a smaller lag to lead vehicle speed changes, ii) a greater THW with smaller variation (i.e. smaller amplitude), and ii) less variation in the InvTTC or equivalently a reduction of the frequency with which short TTCs are experienced (i.e. large negative Inv TTCs). The main effect of the support system is essentially that the combined driver plus system operate at a longer THW and is more vigilant than the driver alone.

So far the effect of THW and InvTTC separately has been shows but it was also shown that the frequency of very small THWs was not reduced for about half the subjects (0.5 percentile in Figure 6). The question was whether a shift from closing to opening small THWs took plane. This can be assessed with a 2D CDF where THW is set along the x-axis and InvTTC along the y-axis and all samples are put in bins as shown in Figure 12. White indicates many samples and black few samples in a bin.

Figure 12 shows the raw data. It shows the distribution of (THW,InvTTC) observations for the baseline condition in the top panel and for the support system condition in the middle panel. From these two figures it is immediately clear that a shift to longer THWs took place and that the frequency of rapid closing (highly negative InvTTCs) and rapid opening (highly positive InvTTC) are reduced in the supported condition. This is consistent with the time response to the sinusoidal lead vehicle speed profile in Figure 11.

The bottom panel of Figure 12 shows the difference between the two normalized distributions. It only shows where a decrease in the normalized number of samples occurred. It is clear that the main effect is a reduction of short THWs and a reduction of rapidly closing gaps (i.e. large negative InvTTCs).

Another observation is that the support distribution is more tightly clustered around the mode than the baseline distribution. This suggests that the system plus driver controller has a higher bandwidth than the driver alone. Again this is consistent with the model based analysis.

Given that the raw data includes the effects of natural variability in driver vigilance and thus response urgency as well as the effect of differences in the distribution of lead vehicle velocity profiles, the fundamental effect of the support system on the distribution is not as clear as one would obtain by looking at the model output. Therefore, the 5 coefficient composite model was run on the data. To increase the clarity of the effect the baseline model was run on all lead vehicle segments (i.e. those from baseline and those from support condition) and similarly the support condition model was also ran on all baseline and support condition lead vehicle profiles. The resulting distributions are shown in Figure 13. The top panel shows the baseline condition and the bottom panel the support condition.

From Figure 13 it is clear that the support system very effectively:

- Increases the target THW (i.e. the mode of the distribution)
- Removes all rapidly closing situations at short THWs (i.e. lower left portion of the baseline distribution not present with support system)
- Reduces all fast opening situations (i.e. the upper portion of the distribution).
- Tightens control (i.e. the distribution of more clustered around the target THW).

These results indicate very clearly that the driver plus support system operates as a highly effective controller capable of reducing the frequency with which undesirable situations are encountered.

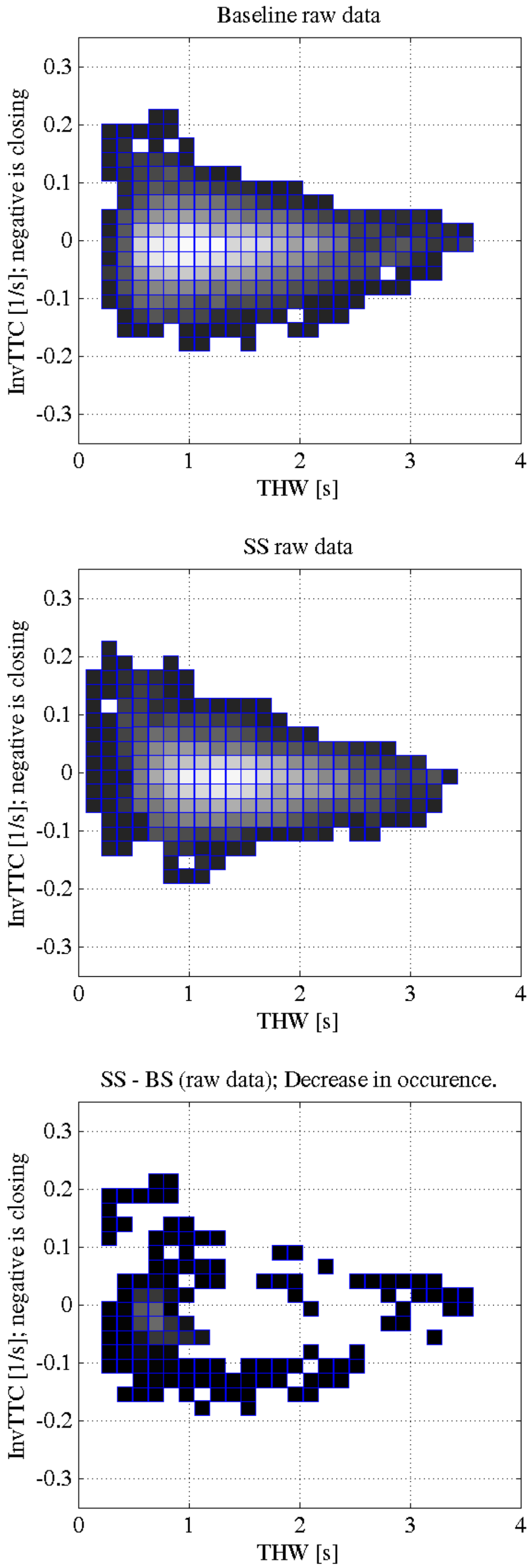


Figure 12. Distribution of all raw data samples in the THW, InvTTC phase plane. The top panel shows the distribution for the baseline (BS) condition; the middle panel for the support system condition; and the bottom panel shows the difference between the two indicating where the support system reduced the frequency of occurrence. White indicates many samples and black very few samples. A non-linear mapping to gray-scales was employed (i.e. normalized cumulative number of samples powered by 0.35) to obtain better insight into the shape of the distribution.

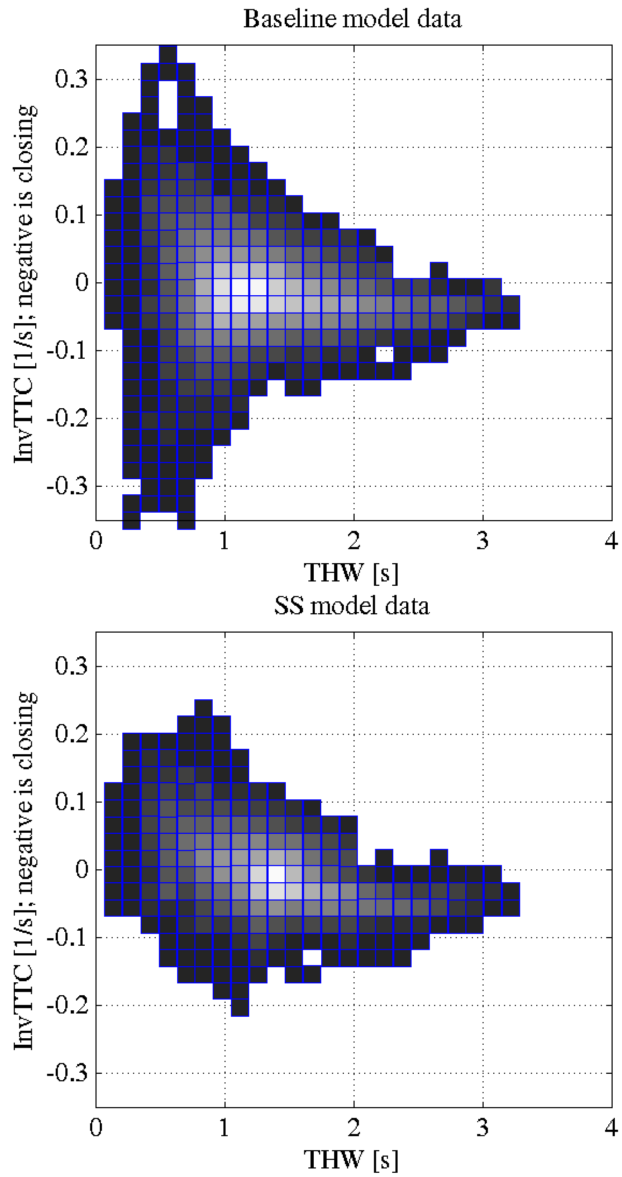


Figure 13. Similar to figure 12 but for model output rather than raw samples. The baseline composite model was run on all lead vehicle speed profiles (including those from baseline and support system data). Similarly the composite support was also run on all available lead vehicle data. The top panel shows the distribution for the baseline condition and the bottom panel for the support system condition.

CONCLUSION

A prototype driver support system with accelerator pedal force and driving and brake force control has been discussed in the context of its effect on control of the gap to a lead vehicle as measured in a field experiment. A model-based approach was adopted to gain deep causal insights into the ways in which the support system alters how the driver plus system responds differently to gap changes than the unsupported driver. Focus was directed to car following on urban freeways. The results suggest that the combined driver plus support system responds faster and stronger to lead vehicle deceleration. The driver plus support system is able to avoid not only rapid closing but also rapid opening suggesting that the driver plus support system does not exhibit the same over-reactions to undesirable situations that are seen in the unsupported condition. The driver plus support system is able to keep the gap closer to its desired size.

The driver support system has demonstrated to aid drivers considerably in their effort to maintain an acceptable gap to a lead vehicle. The combination of integrated perceptual and control support offers drivers a means to flexibly mange their safety-margins as their needs and contextual conditions change. The augmented driving ecology presented by the system is a natural extension of the existing driving ecology that gives drivers the flexibility and freedom to decide what is acceptable and react to violations in an efficient manner.

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