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AFFORDING REALISTIC STOPPING BEHAVIOR: A CARDINAL CHALLENGE FOR DRIVING SIMULATORS

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ABSTRACT

Drivers adopt nearly constant deceleration rates when intending to stop at a distant target. In driving simulators however we often observe different control strategies. Depending on simulator fidelity, deceleration profiles range from saw-tooths to multi-modal profiles to profiles that do resemble those seen in reality. These deviations from reality suggest that drivers have difficulty controlling their vehicle based on the assumption that a constant deceleration rate (approximately constant brake pedal depression) is most efficient at least from a control and attention point of view. The discrepancy between reality and simulation is attributed to the fact that perception of distance, speed, and acceleration, as well as time-to-collision are biased in all current driving simulators (i.e. they are perceived at scaled magnitudes). We introduce a driver model for stopping behavior and demonstrate its capability to reproduce the braking profiles observed in various driving simulators by varying only two model parameters: i) control gain, and ii) the perceived time-to-collision at which braking is initiated. For a given set of simulator dependent perceptual biases in distance, speed, and acceleration estimation, it appears that drivers only need to adapt these two parameters to achieve efficient deceleration, which in some cases takes surprisingly much practice. The reason is attributed to the fact that such a simple adaptation is perceived as counter intuitive when the perceptual biases do not satisfy a particular ratio. If for example, acceleration perception is accurate but speed and distance are severely underestimated then, a simple intuitive adaptation cannot produce efficient braking; in that case, either a heuristic may be needed to decelerate (e.g. brake hard at the last possible moment), tight feedback control may need to be employed (resulting in a non-constant deceleration profile), or a non-intuitive gain adaptation may need to be stumbled on. In exploring the limitations of the model, we derived at the following hypothesis: the optimal scale factor, defined by the ease with which drivers can arrive at an efficient stopping strategy, in a driving simulator is a strong function of the biases in distance, speed, and acceleration perception. The theory underlying this hypothesis is discussed, as are its implications for simulator design and driver distraction research.

1 INTRODUCTION

The constant deceleration rate observed in real life stopping behavior is apparently the most desirable strategy when drivers are slightly hurried. This observation may not hold true under different states of mind as a shift in the balance of various driver needs may push another strategy to the top. A constant deceleration strategy is most efficient from a control theoretic and attention management point of view. In driving simulators, however one often observes multi-modal deceleration profiles (Suetomi & Kido, 1995; Boer et al. 2000), which we believe are undesirable to drivers. During these stopping episodes, drivers apparently realize that they decelerated too hard

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initially and have to reduce the deceleration rate to avoid a premature stop. In some cases, the mis-judgement or mis-implementation of the required initial deceleration rate is so severe that drivers temporarily feel the need to press the accelerator pedal during a stopping maneuver in order to shorten the total stopping time. Three questions arise that will be addressed in this paper: i) what causes these aberrant deceleration profiles, ii) how can we model stopping behavior in driving simulators from a human centered point of view, and iii) how can we use this model to improve simulators and understand their limitations in providing insight into real world driving behavior. Focus is placed on the role of perceptual biases in distance, speed, and acceleration perception on stopping behavior (i.e. the initiation decision and control) and drivers' ability to adopt efficient stopping in a simulator with biased perception.

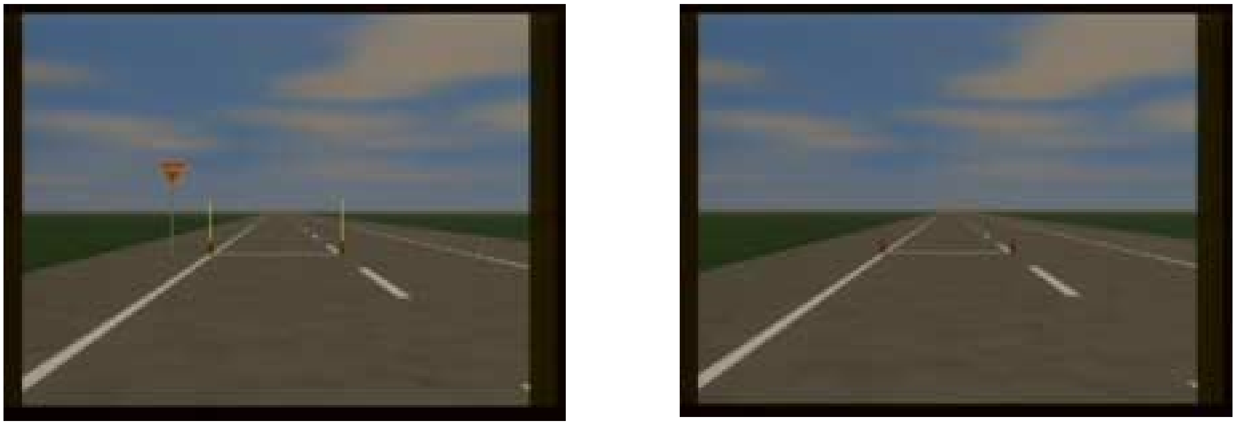

FIGURE 1. Image of stop line with stop sign (left) and without stop sign (right) from a distance of 20m in the Nissan Research Center Driving Simulator. The lane width is 3.5m, the width of the white line is 0.2m, the cones are 0.3m high, and the driver's eye-point is at a height of 1.2m.

In most simulators, drivers experience differences between expected and observed control consequences. They sense that the simulator does not reproduce the driving experience accurately. This mismatch is observed in speed perception (Sidaway et al., 1996), time to collision perception (Cavallo et al., 1997), and in longitudinal and lateral control. The latter is attributed to the cost associated with accurately representing sustained longitudinal and lateral decelerations as well as representing accelerations at veridical magnitudes. Therefore, in most simulators, motion is either not reproduced (i.e. fixed base simulators) or reproduced at a scaled level. Because simulator drivers perceive distance, speed, time to contact, and accelerations in scaled forms, they need to adapt their behavior (retune their decision criteria and controllers) so as to arrive at an efficient, safe, and comfortable behavior again. In some cases, this cannot be achieved and the question we address here is why. For example, why do some subjects always exhibit multi modal deceleration profiles when stopping at a target even after weeks of practice. When perception is highly biased, feedback control can be much more attention demanding than the real world equivalent. This mode of control can be likened to that of a novice driver. The degree to which drivers need to increase their attention to the driving task has important consequences for driver distraction studies because the driving task itself is now more demanding than in reality thus altering the available attentional resources for performing in-vehicle tasks.

2 ACCELERATORY FORCES IN DRIVING SIMULATORS

Stopping behavior is one of the most difficult driving tasks to simulate well in driving simulators. To fully reproduce the longitudinal deceleration rates observed in stopping behavior from an initial speed of 80kph requires a longitudinal sliding rail in excess of 100m even if the maximum perceptually constraint tilt coordination is adopted. This cost prohibitive factor is one reason why all simulators reproduce acceleratory forces on the driver only to scale (generally less than half of what they are in reality). The onset of a hard braking maneuver is also costly to simulate in a driving simulator because of the required high bandwidth. Even though tilt coordination can be used very effectively for low bandwidth maneuvers, high bandwidth maneuvers require sliding rails to carry out the sustained acceleration while tilt gradually takes over (the key issue is to keep the tilt rate below human perceptual thresholds). Simulators without a sliding rail, even if they have a moderately sized hexapod 6-DOF moving base cannot use much tilt coordination to trick the visual-vestibular system into perceiving a forward tilt as a sustained deceleration.

The maximum tilt is limited by how much one can tilt the cab at sub-threshold rate while the driver is being accelerated linearly as well as by the tilt beyond which tilt is perceived as tilt and no longer as a sustained deceleration (about 30 degrees or 0.5g). The latter depends on the degree to which the visual and auditory scenes support sustained deceleration and the degree to which subjects are visually dominant. Note that deceleration in a stopping maneuver is about 0.5g and can thus be simulated using tilt-coordination. The problem for most simulators is that the time within which this maximum acceleration is achieved is too short to tilt the cab far enough with out the driver noticing it.

In addition to using tilt as a proxy for sustained deceleration, simulators are characterized by a scale factor: the fraction of the visually presented acceleration that is represented by the moving base. For example, a scale factor of 0.4 means that a deceleration rate of $6\, m/s^2$ is simulated by the moving base as $2.4\, m/s^2$. As long as the limited perceptual channels are accurately simulated, drivers are assumed minimally affected by such a scaling[1]. Research shows that a scale-factor of about 0.5 is optimal in terms of perceptual congruency and controllability (Satoh et al., 1994). We explore some potential factors for this fact beyond the obvious one that is related to people's perception of tilt angle and rotation rate.

We hypothesize that one of the sources for this subjectively ideal scale-factor of about 0.5 is the incompatibility of biases in distance, speed, and acceleration perception. It is assumed that drivers perceive these quantities at scaled magnitudes. The term 'bias' is used to refer to such magnitude scaling. Our expectation is that the optimal scale-factor could have been much smaller or greater if a different audio-visual system were used or the audio-visual environment were rendered differently. In this paper, focus is placed on stopping behavior for which we postulate the following hypothesis:

> ***Hypothesis:*** *When the square of the perceptual bias in speed divided by the perceptual bias in distance equals the perceptual bias in acceleration, then simulator drivers can easily adapt the control strategy learned in reality and achieve efficient stopping behavior that closely resembles their behavior in reality.*

Similar hypotheses can be established for other driving tasks, such as for curve negotiation and time to collision estimation. The one for time to collision is simply that the perceptual bias in distance and speed need to be identical for time to collision to be perceived veridically. A perceptual bias hypothesis for curve negotiation is more difficult to establish as it depends on the particular visual cue that drivers use as well as the fact that jerk plays a very important role as a lead-equalizer for lateral control. The problem lies in the fact that higher order visual and vestibular dynamics play a crucial role. This topic will be explored in a future paper.

Humans are notoriously bad at accurately and quickly perceiving accelerations based on purely visual information. Furthermore, the visual system is generally too slow for effective control of balance and fast ego-motion; for this we rely to a large degree on other sensory systems such as our vestibular organ and/or proprioceptive sensors. Thus, what do drivers use in fixed base driving simulators? Fortunately, vision can be used to deduce deceleration (note that the vestibular system offers direct perception of deceleration) and that other cues such as sound and in some cases steering and or seat vibrations facilitate deduction of speed changes and therefore decelerations. All these cues combined provide at least some sense of decelerating or accelerating.

The question is what are the perceptual scaling factors for distance, speed, and acceleration in a fixed-base driving simulator. How this can be measured is left as topic for future research. In this paper, we propose a model capable of predicting whether drivers should be able to adapt to a natural deceleration strategy in full stopping behavior for a given set of perceptual scale factors on distance, speed, and acceleration. Note that a simulator's scale factor is the ratio between acceleration measured in the simulator and those measured in reality for the same set of maneuvers.

3 DO WE UNDERSTAND HOW AND WHY DRIVING BEHAVIOR IN SIMULATORS DIFFERS FROM REALITY?

First and foremost, there is a serious lack of validation studies published in readily accessible sources. This greatly limits our ability to develop models useful for predicting driving behavior in simulators and thus also limits our

[1] The degree to which this assumption is true can only be established by comparing results from the same drivers driving the same car in the same environment under the same conditions in reality and in the simulator (e.g. Boer et. al, 2000). The key to analyzing the results is to adopt a driver-centered rather than an engineering-centered approach. Simple measures such as variability in lateral deviation and speed are insufficient. The key is to use decision, control, and performance variables that drivers use rather than what is mathematically convenient (Boer, 1999).

ability to determine to what degree simulator results can be applied to reality. Boer et al. (2000) present a detailed driver centered discussion of the differences observed when the same drivers drive the same road in the simulator and in reality[2]. Part of that study focused on stopping behavior. Here, we expand on the stopping component by providing a model-based analysis of stopping data obtained in our moving base driving simulator. We were unsuccessful in locating papers that present predictive models that explain why drivers have more difficulty controlling their vehicle in a simulator than in reality. The main issue addressed here is whether a simple proportional controller operating on a set of perceptually biased input variables is capable of explaining and reproducing the various braking strategies observed in our moving base driving simulator as well as other profiles seen in the open literature. The model predicts the decision when drivers initiate deceleration as well as how to they decelerate based on a set of perceptual biases. By estimating these biases in distance, speed, time to contact, and acceleration experimentally for a given driving simulator, the model predicts whether drivers will be able to employ an efficient stopping control strategy.

In follow up studies we plan to validate the proposed perceptually-plausible model with data from various driving simulators with different levels of fidelity. The intent is to gain a fundamental understanding about the curious interactions that causes some low fidelity simulators to produce apparently more realistic stopping behavior than some higher fidelity simulators (based in informal discussions with driving simulator colleagues). The proposed model encapsulates our understanding about the interaction between various perceptual cues that mediate realistic stopping behavior. The assumption, that more fidelity produces a better match between simulator and reality may not hold true especially if fidelity is not increased equivalently along the visual, motion, and sound dimension. The ultimate goal is to configure driving simulators such that realistic driving behavior is elicited that does not demand excessive workload. This should be used as a definition of fidelity. Based on this definition it is clear that fidelity is driver task dependent.

4 BACKGROUND EQUATIONS

Familiar Newtonian mechanics states that the distance to an object changes as follows when deceleration a is kept constant (a is positive for deceleration)

$$\begin{aligned} d_t &= d_0 - v_0 t + \frac{1}{2} a t^2 \\ v_t &= v_0 - at \end{aligned} \tag{1}$$

where d_0 is the initial distance to the target and v_0 the initial velocity. The time-to-stopping or TTS (τ_S) is simply

$$\tau_S = \frac{v_0}{a} \tag{2}$$

By substituting τ_s for t in Eqn. (1) and setting d and v to zero (i.e. the stopped final state) we obtain an expression for the required constant deceleration rate

$$a = \frac{v_0^2}{2d_0} = \frac{v_0}{2\tau_C} = \frac{d}{2\tau_C^2} \tag{3}$$

Manipulating equations (2) and (3) with the following equation for time-to-collision TTC (τ_C)

$$\tau_C = \frac{d_0}{v_0} \tag{4}$$

results in the following relationship between TTC and TTS

$$\tau_S = 2\tau_C$$

Note that TTC is the time it would take the vehicle to reach the stopping target if the current speed were maintained. Note also that the equation for TTC always holds but that the equation for TTS only holds for sustained constant deceleration.

[2] Seldom do researchers publish sufficient information to assess what the behavioral biases are that their driving simulator introduces. To some degree this is attributable to the adopted analysis (i.e. engineering centered rather than driver centered) and partly because negative results are generally shunned even though in this case they enhance our understanding about what makes a great driving simulator more than positive results do.

5 SIMULATOR STUDY OF STOPPING BEHAVIOR

The following experiment was designed to determine how drivers decelerate to a full stop in Nissan's moving base driving simulator (Fig. 2). This study was inspired by the study reported in Boer et al. (2000) in which we found that subjects initiate deceleration later, reach a higher maximum deceleration rate, and exhibit a multi modal deceleration profile in the simulator even though the same six subjects adopted a constant deceleration profile in reality. It should be stressed that stopping is extremely challenging for all driving simulators and that all simulators offer high value in terms enhancing our understanding of driver behavior under a wide range of less challenging conditions whose scope depends on simulator.

5.1 Experimental Design

We took two of the subjects from Boer et al. (2000), and added two expert and two novice driving simulator drivers for the present study. The experiment consisted of three session: i) normal braking gain (brake gain 1.0), ii) braking with a brake pedal gain of 0.5 (brake gain 0.5), and iii) normal braking gain with the added task to release of the gas pedal as soon as the stop line was detected (detect). The latter was added to make sure that the stop line was indeed visible early enough and that the observed delayed deceleration onset in the simulator was not caused by the inability to see the stop line early enough.

Six male drivers participated in the experiment. Their driving simulator expert status together with the order in which they ran the sessions are shown in Table 1. Each session consisted of driving down the left lane (3.5m wide) of a straight road on which a stop line with or without a stop sign was placed every 500m. In each trial, a subject stopped 12 times. Half the stop lines also had a stop sign and poles (left panel in Fig. 1) and the other half only had the stop line with two pylons (right panel in Fig. 1). In this paper, we report only on the results from sessions with a brake gain of 1.0 and only on the stopping behaviors to a stop line flanked by a stop sign, pylons, and poles (i.e. six stops per subject). This choice assures that detection is not an issue as it may have been without the poles and stop sign (a 30cm cone at 100m distance for our display would span about 3.5 pixels which is detectable especially given that the subjects were looking for it). The 20cm wide stop line itself however will not be clearly visible at such distances. Its width projects to less than one pixel, which means that the row of pixels around the line will only be slightly lighter and thus the line will appear at very low contrast. This is why we supplemented the line by cones.

TABLE 1. Driving simulator expert rating (higher number is more expertise) of the six subjects and the order in which they participated in the three experiment sessions.

Subjects	Driving Simulator Expertise Rating	Order of Trials		
		Gain 0.5	Gain 1.0	Detect Always last
	[1-10]	[1-2]	[1-2]	[3]
On (5)	8	2	1	3
Ta (6)	10	1	2	3
Ha (1)	8	1	2	3
Ma (3)	10	2	1	3
Ki (2)	1	2	1	3
Ne (4)	3	1	2	3

All subjects received a 10-stop training trial prior to data collection. Those who were given a gain of 0.5 first, trained with this gain. Subjects had no additional training between switching from one gain setting to the other. They were all instructed to drive at about 70kph between stop lines.

5.2 The Nissan Research Center 6-DOF Driving Simulator

The three linear and three rotational accelerations are simulated with a hexapod cooperative motor-driven system (non sliding rail). We did not use tilt-coordination to simulate sustained deceleration. Linear onset movement was simulated with a scale factor of 0.5. Actual vehicle roll and pitch were modeled up to about 5 degrees. The visual scene is projected onto 3 screens that provide a 120 degree horizontal and 30 degree vertical field of view (visual resolution was 0.05deg/pixel). Distance from driver to screen is about 3.4m and the driver's eye height is assumed at 1.2m. The driving experience is further enhanced by a digital sound system that simulates the various sound sources (e.g. engine, wind, tire). The relationship between brake pedal pressure and vehicle deceleration were matched closely to reality. A photograph of the system is shown in Fig. 2

5.3 The Stopping Profiles from Six Subjects

The median profiles of each subject of several variables are shown in Fig. 3 as a function of time to stand-still (left column) and distance to stop-line (right column). Drivers exhibit large individual differences but are highly self-consistent. Their distinct stopping strategies can be categorized into three groups that appear to be roughly related to the subject's level of expertise in driving the simulator. Fig. 3 shows that:

1. Expert Driving Simulator Drivers (top three profiles in the upper left panel) show a constant deceleration profile and a shorter brake onset TTC than the other subjects.
2. Novice Driving Simulator Drivers (middle two profiles in the upper left panel) exhibit a multi modal deceleration profile and an earlier bake pedal onset time than the expert group.
3. The Intermediate Subject (lower profile in the upper left panel) exhibits a highly pronounced bi-modal deceleration profile with an onset TTC between the groups labeled experts and those labeled novices.

5.3.1 The intermediate subject (Ha) was an expert but apparently had not reached the same level of deceleration efficiency as the other experts.

FIGURE 2. Nissan Research Center Moving Base Driving Simulator (see text for details).

5.4 Learning to Drive the Simulator

The question is how do drivers adapt their braking strategy as they gain experience with the simulator? Clearly, a constant brake pedal depression is most efficient. This open loop strategy requires minimal attentional effort but most accurate perception. In the real world, drivers know how much to press the brake pedal to come to a full stop at a desired distance down the road. In the simulator, this learned mapping no longer holds because of compromised visual, auditory, and vestibular stimulation. Interestingly, if the control strategy were purely open loop, then vestibular input should have no effect on their braking profile because the vestibular system is not activated when the decision to initiate deceleration is made. It is plausible that drivers use the vestibular system only during the initial phase to establish the desired deceleration rate and then simply maintain that; this tight feedback control is used for a short time interval only. This suggests a mapping from perceived speed and distance or time-to-collision to a desired vestibular signal or desired deceleration rate. If the vestibular signal is not present or scaled down compared to reality (the case in most simulators), then the driver will decelerate too much. Through a process of adaptation, they either learn to scale down their brake pedal depression to the point where they no longer experience a need to relax the brake pedal towards the end of the maneuver in order to avoid a premature stop or they initiate their deceleration later so that the high deceleration rate does not need to be reduced to come to a full stop at the target line. Experienced subjects appear to adopt the latter strategy as they do exhibit very high deceleration rates and initiate their deceleration later (i.e. at a smaller TTC) than the novices. As will be shown later when we discuss the model, it is possible to attain a constant deceleration profile for a wide range of TTC by simply adopting a lower gain.

The reason why subjects do not adopt such a lower gain is most likely due to the fact that it is inconsistent with their percept and expectations. Their natural response to what they experience in many simulators is to increase their gain partly because the effects of pressing the brake are not perceived as strongly as in a real vehicle and partly due to perceptual biasses. This inconsistency is apparently hard to overcome because otherwise we would see that drivers would quickly adopt a lower gain and initiate deceleration earlier so that they do not have to attain such high deceleration rates. Below we provide a hypothesis that predicts under what perceptual conditions, the perceptual inconsistency may diminish and drivers may be able to employ normal (i.e. non-heuristic) stopping control strategies after a short adaptation period.

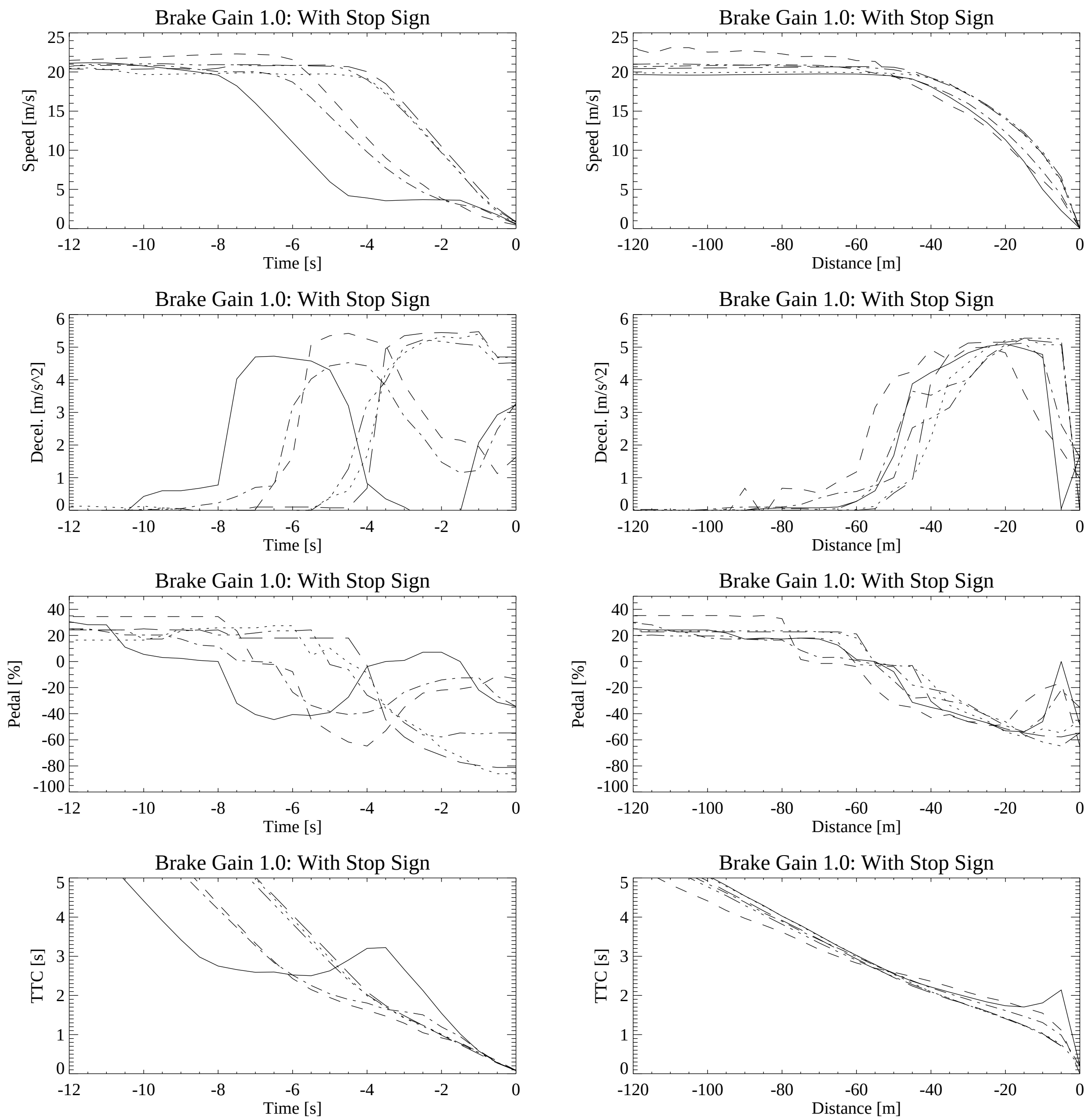

Figure 3. Deceleration profiles for the stop experiment. The various panels show as a function of time to stand still (left column) distance to stop line (right column), the following variables: speed, deceleration rate, pedal movement, and TTC.

5.5 OBSERVED STOPPING BEHAVIOR

The driving task of stopping at a distant target such as a stop line comprises of two stages: 1) detect the stop line and determine when to initiate deceleration, and 2) control deceleration rate such that the vehicle stops at the stop line. Detection is assumed to precede the point at which drivers prefer to initiate deceleration so that they can adopt a preferred deceleration rate. If this is not the case, aberrant deceleration profiles are expected. The preferred deceleration rate is assumed based on a satisficing compromise between *motivating and constraining needs*. The two *constraining needs* are comfort and safety; they drive the maximum deceleration rate down. Driving is also based on *motivating needs* of which expediency is most relevant[3]. Expediency causes drivers to delay initiation of the deceleration thereby increasing the maximum deceleration rate. Drivers are assumed to adopt a satisficing decision strategy that causes them to accept a range of onset conditions for which their constraining needs are satisfied (i.e. they do not exceed a driver dependent threshold) and for which their motivating needs are satisfied (i.e. they do exceed a driver dependant aspiration level)[4].

From our study described in (Boer et al., 2000) we know that drivers naturally initiate their deceleration (begin to take foot off gas pedal) at a time-to-collision of about $5.5s$ with an approach speed of about $17\,m/s$ (about 60kph) and that they adopt a constant deceleration rate of about $3\,m/s^2$ and a total stopping time of about $9s$. The constant deceleration rate is reached in about $2.5s$ which includes the time to take the foot off the gas pedal and move it to the brake pedal and begin to press the brake pedal. Drivers begin to depress the brake pedal at a time-to-collision of about $4s$.

5.6 CONTROL THEORY OF BRAKING IN A DRIVING SIMULATOR

Humans continuously establish predictive expectations for subsequent verification. This innate process is the foundation of efficient control, adaptation, and learning. Learning is the process of establishing a strategy whereas adaptation is the fine-tuning of coefficients that characterize the strategy. In case of our model, the structure is the proportional stationary linear controller (i.e. $du = k_p e$), with k_p as the only coefficient. For this simple model, control adaptation is limited to adopting different values for k_p. In the section, the issues surrounding the proposed control model are presented.

5.7 ***Tau*** **and** ***Tau-Dot*** **or Distance, Speed, and Acceleration**

A complex of questions that have been debated for over a decade are related to what perceptual cues drivers use in braking to a full stop. More specifically, do drivers use time-to-collision (*tau*) in detection and do they use the rate of change in time-to-collision (*tau-dot*) in control. The assumption is that *tau* is directly perceived. If that is indeed so, then visual fidelity should not have a significant effect on driver's estimation of time-to-collision[5]. Unfortunately for the driving simulator community, this is not the case and many researchers have clearly demonstrated that *tau* is a strong function of simulator fidelity (Cavallo, 1997; Probst, 1986). In fact, their results seem to suggest that *tau* is derived at by perceiving distance and speed separately and taking their ratio (*tau* equals distance/speed). Similarly, if *tau-dot* were the primary cue used in controlling stopping behavior, then there should be no effect of a moving base. In fact, a moving base would not be necessary in simulating longitudinal deceleration. Clearly, a moving base is needed as drivers do behave very differently in fixed base driving simulators than in reality (Suetomi & Kido, 1995; Boer et al., 2000). This alone is evidence that *tau-dot* is not the whole story. Some people in support of the *tau-dot* theory seem to ignore the fact that a constant deceleration control strategy automatically follows the *tau-dot* theory which states that drivers regulate *tau-dot* around $-1/2$ (Flach, 1999). The fact that drivers do adopt a constant deceleration strategy does not mean that they use *tau-dot* as a control input variable. In this paper we propose a simple braking strategy that depends on distance, speed, and acceleration perceptions and show that biases in these perceptions (e.g. underestimation of speed in driving simulators) do result in the observed changes in stopping behavior when comparing reality and simulation. We assume that distance,

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[3] See Boer et al. (1998) and Boer et al. (1998b) for a full account of how drivers' motivational (expedience, pleasure of driving and kick of driving) and constraining (risk, economic cost, comfort, social deviance, and workload) needs shape their behavior.

[4] Note that this could lead to an empty set. In that case drivers relax one of their constraints (e.g. accept a slightly less comfortable deceleration rate) or adapt their behavior (e.g. accept a lower level of expediency or equivalently allowing for more time to come to a full stop).

[5] *Tau* is the ratio of the visual angle of an object or between an object and an ego centered fixed reference (e.g. the bottom of the windshield) and the rate of change in that visual angle. As long as the visual object fits on a screen this percept should not be affected by anything else in the scene. Note that this is not so for speed perception as it is derived from the flow of all objects in the scene.

speed, and acceleration are complex percepts that depend on a multitude of cues from different sensory channels (visual, auditory, vestibular, and kinesthetic).

Before we continue, we first present the derivation of the fact that *tau-dot* equals minus a half when a constant deceleration strategy is adopted. We already introduced that

$$\tau = \tau_C = \frac{d}{v}$$

$$\tau_S = \frac{v}{a}$$

from which we derive the following by differentiation

$$\dot{\tau} = -\left(\frac{v^2 - ad}{v^2}\right) = -\left(1 - \frac{ad}{v^2}\right)$$

where the minus sign signifies the fact that *tau* decreases as time progresses. This equation transforms as follows when a constant deceleration strategy is adopted (using the equations in Sec. 4).

$$\dot{\tau} = -1 + \frac{\tau}{\tau_S} = -1 + \frac{1}{2} = -\frac{1}{2}.$$

Equivalently, if the deceleration rate is constant (i.e. equation for τ_S valid), then τ_C reduces to zero in τ_S seconds which means that $\dot{\tau}_C = -\tau_C / \tau_S = -1/2$. Every τ_C seconds τ_C halves[6].

If we remove the assumption that direct perception means direct perception based on visual angles of the approached object alone, the comparison between our and the *tau-dot* strategy becomes more interesting. For example, if the perception of *tau* and *tau-dot* are functions of speed, distance, presence of vestibular cues, etc., then one has to either question their value as direct percepts or assume that these other cues also play a role and that *tau* and *tau-dot* only play a partial role in mediating decisions and control. Note this does not mean that time-based variables are not extremely important in characterizing driving behavior but that it does mean that driver's percept of time-to-collision and its derivative may partially be shaped by also combining perceptions of other variables such as distance, speed, and acceleration. For the sake of this paper, lets ignore *tau* and *tau-dot* for the moment and see what indirect perception has to offer in terms of explaining the differences in stopping behavior observed between simulation and reality.

6 THE CONTROL MODEL

A model provides a framework for consolidating knowledge and testing hypotheses. Control strategies can be classified as open or closed loop. The primary distinction between open and closed loop is that closed loop control uses feedback continually to moderate control input whereas open loop control uses feedback intermittently to reinstate an updated open loop control sequence. In principle the monitoring/update bandwidth for closed loop control is considerably higher than in open loop control thus requiring more attentional resources. Open and closed loop control mesh together when open loop control is continually evaluated and updated when necessary. In this paper, we focus on a combination or open and closed loop control strategies. The open loop control strategy is used to derive at a target state, which is then maintained through closed loop control.

We decided to adopt a continuous control model partly because we feel that novice simulator drivers are forced into a continuous feedback control strategy. The alternative would be a model with multiple stages, each associated with its own control strategy. A rule-based model is also an option but we wanted to explore to what degree a simple model is capable of reproducing the observed results and whether we can explain their origin. Again, the goal is to

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[6] The fact that the total stopping time is 2τ is also nicely demonstrated by the following series for the total stopping time

$$\tau_S = \tau + \frac{\tau}{2} + \frac{\tau}{4} + \frac{\tau}{8} + \frac{\tau}{16} \ldots = \left\{\sum_{n=0}^{\infty} \left(\frac{1}{2}\right)^n\right\}\tau = \frac{1}{1-1/2}\tau = 2\tau$$

It is also easily shown that the distance to the target reduces to a quarter after τ seconds and that speed halves if the following constant deceleration strategy is employed $a = v^2/2d = v/2\tau$ or one of its mathematically equivalent formulations.

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develop the simplest possible model that is capable of explaining all the observed results and make testable predictions about novel situations.

6.1 The Abstract Decision and Control Strategy

The braking model consists of two components. First a detection stage that models when drivers initiate deceleration for a full stop. Secondly, a control stage where the vehicle is regulated to a full stop at a target location down the road. The model introduced below assumes that deceleration is initiated when time-to-collision τ reaches a certain value and that time-to-collision is perceived as the ratio of distance d and speed v (or accurately modeled as such)

$$\tau = \frac{d}{v}$$

The model furthermore assumes that deceleration is controlled by nulling the difference between the desired constant deceleration rate a^* and the observed deceleration rate a according to

$$du = k_p\left(a^* - a\right)$$

where

$$a^* = \frac{v^2}{2d}$$

and k_p is a fixed proportional control gain.

6.2 The Role of Perceptual Biases

If drivers do indeed use $d, v,$ and a in their decision and control, then any differences in braking behavior between reality and simulation can be attributed to differences in the perception of these variables[7]. It is well known that drivers underestimate distance, speed, and accelerations in virtual environments (Sidaway et al., 1996) and that perceptual biases decrease as fidelity increases (Cavallo et al., 1997). It is also well known that drivers in general are very bad at estimating acceleration, especially longitudinal ones, based on visual information alone (Werkhoven et al., 1992). Based on these facts, we model these perceptual biases by scales on $d, v,$ and a. The perceived values of $d, v,$ and a are

$$d_p = s_d d$$
$$v_p = s_v v$$
$$a_p = s_a a$$

respectively. It is furthermore assumed that $s_d \le s_v \le s_a$ for most simulators[8]. We assume for simplicity that the scaling factors are constant but in fact perceptual biases diminish as the perceived quantities decrease; for example, distance is underestimated beyond 3m and overestimated closer than 3m (Loomis et al., 1996). This simplification is assumed to be one of the sources for small differences between model and observations. In the future we plan to

[7] This assumes that drivers do not adopt an entirely different control strategy in the simulator than in reality. Without concrete evidence for this being the case, we assume that all differences are perceptual. We assume that drivers adopt a linear proportional controller (i.e. a single gain on the error between desired and observed deceleration) but that they are capable of adapting this gain. We do, for example, not assume that driver adopt a non-linear controller whose gain, for example, depends on some perceptual variable.

[8] This is most likely not true for simulators with low fidelity visual/auditory systems but with a high-fidelity motion-systems. In that case s_a may be close to one whereas s_d and s_v may be much less than one. Based on the model, this situation is very difficult to control because a simple gain adaptation does not result in a strategy that yields a constant deceleration rate. Given the cost of motion bases, most systems with a good motion base also have a high fidelity visual system and our assumption is reasonable.

extend our model to incorporate more accurate perceptual biases and identify them for the various Nissan driving simulators.

6.3 Implementation

Drivers adopt essentially a constant deceleration strategy when coming to full stop. This is most efficiently accomplished when a quantity exists that remains invariant through most of the deceleration to a full stop. This quantity is of course the constant deceleration rate itself $a = v^2 / 2d$ and all its mathematical transformations to the perceptual equivalents. The most notable transformation is $a = v/2\tau$. This means that if drivers can perceive either v and d or v and τ, then they can adopt a proportional control strategy. A proportional control strategy, and in essence all control strategies require an error signal, which in this case is the difference between the perceived desired constant deceleration rate and the current perceived deceleration rate. Let's assume that drivers update their deceleration rate (through pedal movements) according to the following a proportional control strategy

$$\begin{aligned} u_n &= u_{n-1} + k_p\left(a^*_{n-1} - a_{n-1}\right) \\ \Delta_{u_n} &= k_p\left(a^*_{n-1} - a_{n-1}\right) \end{aligned},$$

where $a^*_{n-1} = v^2_{n-1} / 2d_{n-1} = v_{n-1}/2\tau_{n-1}$ is the desired deceleration rate based on the perceived state. We make the assumption that drivers know the mapping from desired deceleration to pedal position. In modeling human operators, we can generally not ignore the inherent human delay time and brake dynamics, except under certain preview control conditions. If we assume that the driver has his foot on the pedal, then we do not need to consider the transition time from gas to brake-pedal. This transition time is modeled as part of the decision component. If we assume a human delay of δ time steps (δT_s)[9] and a lag with a cutoff frequency of β radians,that is combination of a neuromuscular lag lumped together with first order longitudinal vehicle dynamics, we obtain the following update equation for vehicle acceleration

$$\begin{aligned} a_n &= e^{-\beta T_s} a_{n-1} + \left(1 - e^{-\beta T_s}\right) u_{n-\delta} \\ v_n &= v_{n-1} + a_n T_s \\ d_n &= d_{n-1} - v_n + \frac{a_n T_s^2}{2} \end{aligned}$$

where the lag is assumed to be concentrated in the response[10].

The brake response was modeled after a real vehicle. The relationship between brake pedal depression and resultant deceleration rate is linear up to a deceleration rate of about $4.5\, m/s^2$ and then the slope drops considerably meaning that a much greater increase in pedal depression is needed to achieve the same increase in deceleration rate. This is modeled as follows:

$$a_n < -4.5 \Rightarrow a_n = -4.5 + 0.4\left(a_n + 4.5\right)$$

The effect of engine braking and other drag forces were lumped together and modeled as a speed dependent deceleration as follows.

$$a_{drag} = -\frac{v_{n-1}}{40}$$

and is added to the a_n update equation as follows

[9] The models are developed in discrete time.
[10] Note that, for linear systems the delay can be placed anywhere in the control loop.

$$a_n = e^{-\beta T_s} a_{n-1} + \left(1 - e^{-\beta T_s}\right) u_{n-\delta} + \left(1 - e^{-\beta T_s}\right) a_{drag}$$

The value of 40 is selected based on the observation that the vehicle decelerated at about $-0.5\, m/s^2$ when coasting at a speed of around $20\, m/s$.

The following perceptual scaling values were assumed

$$\begin{aligned} d_p &= s_d d = 0.8d \\ v_p &= s_v v = 0.6v \quad , \\ a_p &= s_a a = 0.4a \end{aligned}$$

where the perceptual gains for distance and velocity are based on various assumptions. Based on experience with motion and fixed base driving simulators with moderate visual fidelity, drivers tend to underestimate speed by about 40%. In our DSC 2000 study we observed that novice drivers[11] adopted a shorter deceleration onset that was a factor 1.3 shorter than what they exhibited in the instrumented vehicle. This motivated us to assume $s_d = 0.8$ to make the model consistent with an overestimation of TTC of $s_d / s_v = 0.8/0.6 = 1.33$. The perceptual gain for deceleration was simply assumed worse than for velocity by the same degree as velocity perception is worse than distance perception. In this paper we do not report much on the effects of s_d and s_v but primarily focus on the effects of s_a on control. The human delay time was assumed to be $250ms$ (i.e. $\delta = 5T_s, T_s = 50ms$) and a combined human plus system bandwidth was assumed at $4rad$ (i.e. $\beta = 4rad$).

The approach speed in the model was initiatiaized at the observed average approach speed of $75kph = 20.83\, m/s$ and the perceived onset TTC was computed by converting the TTC measured from the subjects' data. The perceived onset delay is simply the scaled measured TTC plus the human delay time

$$\tau_c^{onset} = \frac{s_d}{s_v} \tau_c^{measured} + \delta = 1.33 \tau_c^{measured} + 0.25$$

where τ_c^{onset} is the TTC as perceived by the driver at the time they decide to take their foot off the gas pedal.

Because of the apparent singularity in the error signal when distance goes to zero[12], control is kept constant when the distance drops below 5m (about a car length). This is consistent with the often assumed switch from time based to distance based control as distances decrease.

6.4 Behavioral Predictions with Biased Perception

Predictions derived from the simple are twofold. First braking is initiated later because $\tau_p = d_p / v_p$ is greater than τ and an overestimation of time-to-collision results in a delayed deceleration onset. This is consistent with the earlier mentioned findings in (Cavallo et al., 1997). Secondly, a multi modal deceleration profile is excepted to emerge based on the following causal chain of effects (valid for the assumption that $s_a < s_v^2 / s_d$ ($0.4 < 0.6^2/0.8 = 0.45$)

[11] Expert drivers can not be used for this assessment because they are believed to adapt their brake onset TTC to an artificially low (i.e. not purely perceptually mediated) value to accommodate a simple constant deceleration strategy (i.e. apply near maximum braking).

[12] The singularity is only apparent because 'l Hopital's rule states that the desired deceleration asymptotes to va which is zero when v goes to zero. The real issue is that when the stop line is slightly overshot that the singularity does play a role. It only does not play a role if the vehicle comes to an exact halt at the stop line.

1. The initially perceived acceleration error $\left(a_p^* - a_p\right)$ equals a_p^* because initially the vehicle is not decelerating yet. Furthermore, it is assumed that $s_v^2/s_d < 1$ for most simulators resulting in a smaller than necessary initial pedal depression because a_p^* is underestimated,
2. The smaller than necessary pedal depression results in a rapid increase in e_p because a_p^* quickly increases even though a_p remains small,
3. The rapid and unexpected increase in error signal causes the driver to overcompensate quickly by increasing his control gain k_p (in the simplified model we assume that drivers adapt this control gain from the start because they already adapted their strategy from the first few trials),
4. The excessive control gain causes a larger than necessary deceleration (in many cases close to the maximum of around $5.5\,m/s^2$). It is easily seen that when $s_a < s_v^2/s_d$ that the adopted deceleration rate is greater than necessary, because the error signal is positively biased (see also Sec. 7).
5. After having sustained the larger than necessary deceleration rate they realize that they will come to a premature stop if they maintain the current deceleration rate; they realize this because the error changes sign rapidly (the time it takes them to realize this and therefore the depth of the modulation depends on the difference between s_v^2/s_d and s_a),
6. They overcompensate again in reducing the brake pedal depression because of the excessive gain[13],
7. This causes them to travel too fast again forcing them to depress the brake pedal once more when the error changes sign again[14].

The key components in this process are: i) adoption of a control strategy that works in reality in a situation where key perceptual cues are underestimated, ii) perception that the applied control is insufficient followed by a rapid adaptation of the control gain (i.e. increase in pedal depression), iii) delayed realization of overcompensation that is also overreacted to because of the adopted higher gain, and iv) a final control response to stop the vehicle. In this last stage the distance is rather small and velocity low, which may be associated with different perceptual biases (Loomis et al., 1996[15]). In the detailed mathematical model described above we assumed for simplicity and to promote insight that the perceptual biases are constant throughout the stopping maneuver and that drivers immediately adopt a larger control gain. The latter is motivated by the fact that the realization of a discrepancy between expected and perceived deceleration occurs very early on in the response and the adaptation, as described above, only happens in the first few stopping maneuvers.

The multi-modal braking profile is expected to be particularly prevalent when $s_a < s_v^2/s_d$ and we expect that different types of braking profiles become more prevalent when this relationship is not true. This will be elaborated on in Section 7.

6.5 Model Identification

In order gain insight in the degree to which the model is capable of reproducing the observed deceleration profiles, we established one criteria for each of the three classes of deceleration profiles described in Section 5.3 and shown in Fig. 3. Only model gain and onset TTC threshold were adjusted to reproduce each class' behavior with the model. The criteria are

1. Bimodal with a minimum deceleration in between the two peaks of about $1\,m/s^2$. These are primarily produced by novice simulator drivers.
2. Bi-modal with foot off the brake pedal for about one second. This is the profile of the intermediate subject.
3. Reality resembling. This case shows a nearly constant deceleration profile with a drop in deceleration rate of about $1\,m/s^2$ towards the end of the stopping maneuver. These are primarily produced by expert driving simulator drivers.

[13] This over compensation could be reduced by adopting a lead equalizer. However, that would require perception of the rate of change in error which is not plausible for humans.

[14] In some cases, we observed multiple modes but in general we only observed one. It may be that subjects who show multiple peaks in their deceleration profile have adopted a very tight feedback control strategy as well as a short delay time.

[15] In virtual environments near distances (egocentric space) are generally over estimated and far distances (exocentric space) underestimated.

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The goal was to demonstrate that the same model structure can be used to explain the origin of the three types of deceleration profiles we observed in our data.

Figure 4 shows the proposed model's response for an initial velocity of 75kph for three different control gains and three different brake onset TTCs. These model coefficient values were selected such that the model results closely resembled those of the three classes shown in Fig. 3 using the three corresponding matching criteria. The other model coefficients were fixed to the values given in Section 6.3.

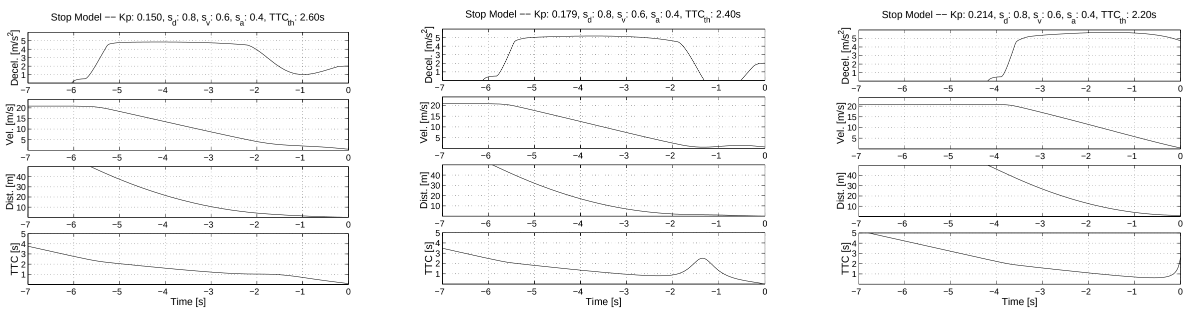

Figure 4. Model predicted deceleration profiles. The control gain and brake onset TTC were selected to achieve a close match to the experimental observations depicted in Figure 3. The left panel reproduces the results for the novice simulator drivers. The middle panel simulates that of the intermediate subject and the right panel deceleration profiles closely resemble those exhibited by the expert subjects.

From Fig. 4, it is clear that the model is capable of reproducing the result of the intermediate subject who takes his foot off the brake pedal and actually accelerates the vehicle during the stopping maneuver (middle panel Fig. 4). This does not require any extra terms in the controller even though it appears a behavior mediated at the tactical or rule base level rather than at the operational or execution level. This excessive pedal behavior is simply accomplished by adopting a gain in between the one that results in a constant deceleration profile and the larger one that produces the multi modal behavior of the novice drivers. The onset TTC of the intermediate subjects also falls between that for the the novice and expert classes.

Given that the intermediate subject is an expert and that his gain and onset TTC fall in between those of the novice and expert drivers, it is tempting to hypothesize that he has partially adapted toward the expert strategy but has not delayed his deceleration onset time and increased his gain enough. The natural tendency for adaptation to an experienced multi modal deceleration profile is to initiate deceleration later. But at the same time the gain also needs to be increased. Thus it appears reasonable to assume that subjects go through multiple learning stages as they are exposed to the driving simulator. This is why we placed the intermediate subject in the middle panel with the novices to the left and the experts to the right. It is entirely possible that different people achieve expert status at with different amounts of exposure to the simulator. The rating in Table 1 is simply based on the number of experiments and testing they participated in.

From Fig. 4 it is clear that all three behaviors shown in Fig. 3 can be reproduced by using different gains and brake onset TTCs. The following similarities were not explicitly sought in the above mentioned three matching criteria but simply emerged:

1. The maximum deceleration rate of the expert drivers (right panel Fig 4) is higher than that of the other subjects.
2. The maximum deceleration rate in the second mode is always less than that observed in the first mode for non-expert drivers (left and middle panels in Fig. 4).
3. The rate at which deceleration decreases at the end of the first mode is less for novice subjects than for the intermediate subject.

Besides the encouraging number of similarities between human and model for such a rather simple model, the following primary difference emerged. The duration of the first mode is longer in the model. This may simply be due to the fact that human drivers, unlike our simple model, do not wait until the error signal changes sign but that they predict this earlier based on the rate of change in error signal (deceleration rate quickly decreases when the error signal changes sign). This suggest that drivers behaved as if they also had a differential error term in their control strategy. The degree to which such a PD-controller rather than the P-controller we assumed is capable of

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producing a better fit is topic of further study[16]. In this paper, we purposefully did not over-parameterize the model because we felt that limitations of the lowest possible model order that provides solid insights should be explored first before higher orders are justified. Note that a highly over parameterized model can always fit the data (e.g. most neural nets).

6.6 Exploring Model Characteristics

6.6.1 Effect of Control Gain and Onset TTC

To provide insight into the effect of model coefficient values on model behavior for a given set of perceptual scaling factors, three different brake onset TTCs were assumed (2.2, 2.4, and 2.6s) and for each, the control gain was adapted to generate, as closely as possible, the three deceleration profiles described in the criteria listed above for the profiles shown in Fig. 3.

Based on the assumption that the model represents human capabilities and limitations, Fig. 5 shows that humans theoretically should be able to adopt a more or less constant deceleration profile for a range of onset TTCs. The fact experienced drivers have a significantly shorter onset TTC than less experienced drivers suggests that onset TTC and control gain are adapted jointly to reach expert status rather than onset TTC or control gain alone as would have been sufficient based on model predictions. One possible adaptation process toward an efficient constant deceleration profile is depicted in Fig. 4 going from the lower right to the upper left panel: drivers increase control gain and shorten onset TTC with prolonged exposure to the driving simulator. The reason why drivers apparently have difficulty adapting quickly to an efficient constant deceleration strategy is explained in Section 7. The question is why do they not simply adopt a lower gain for the perceived onset TTC they use in reality (i.e. adapting from the bottom to the top row).

6.6.2 Effect of Perceptual Scaling Factors

So far, only the effect of control gain and onset TTC on deceleration profiles has been shown for a fixed set of perceptual scaling factors (i.e. $s_d = 0.8, s_v = 0.6, s_a = 0.4$). In this section, we provide insight in to the effect of these scaling factors. In reality it is assumed that $s_a = s_v^2 / s_d$. In both columns of Fig. 6 this perceptual scaling equality holds. Note that this was not so in the simulations described above. The right column corresponds to reality where all three perceptual scaling factors are one. In the left column, the perceptual scaling factors for distance and speed are as before but the perceptual acceleration scaling is 0.45 instead of 0.4 to assure that the perceptual scaling quality holds ($s_a = 0.45 = s_v^2 / s_d = 0.6^2 / 0.8$). We see that the same deceleration profiles emerge when the control gain in the left column is about $1.0/0.45 = 2.2$ times that of reality (right column). The true gain ratio that was necessary to produce nearly identical profiles between the two cases is 2.5. This is attributed to the fact that in the left panel, TTC was overestimated by a factor $s_d / s_v = 0.8/0.6 = 1.3$ which means that deceleration was initiated later than in the right column. We see that the total stopping time (x-axis) is longer in the perceptually scaled case (left column) and that the maximum deceleration rate is also slightly larger. In other words, even when drives are able to quickly adapt they control gain when $s_a = s_v^2 / s_d$ is true, they still overestimate TTC, which causes them to initiate deceleration later and thus forces them into a higher deceleration rate than normal.

6.6.3 Heuristics

The model results are encouraging and do appear to provide a plausible explanation of why expert drivers adopt the stopping strategy they do. However, it may also be that expert drivers have given up on trying to adapt their controller and have simply adopted a heuristic strategy that seems to work and is not mentally demanding. They may simply have adopted an onset TTC that results in a full stop if the brakes are pressed maximally or up to some constant level when they perceive their onset TTC. Whether this is true or not cannot be determined based the limited amount of data we have. Future studies are expected to shed more light on the possibilities of heuristics.

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[16] Other sources will also be explored once we have developed a robust algorithm to perform automatic model coefficient identification on this non-linear model. The Simplex approach, which is assumed highly robust (Press et al., 1990), did not converge satisfactorily most likely because of a number of local minima.

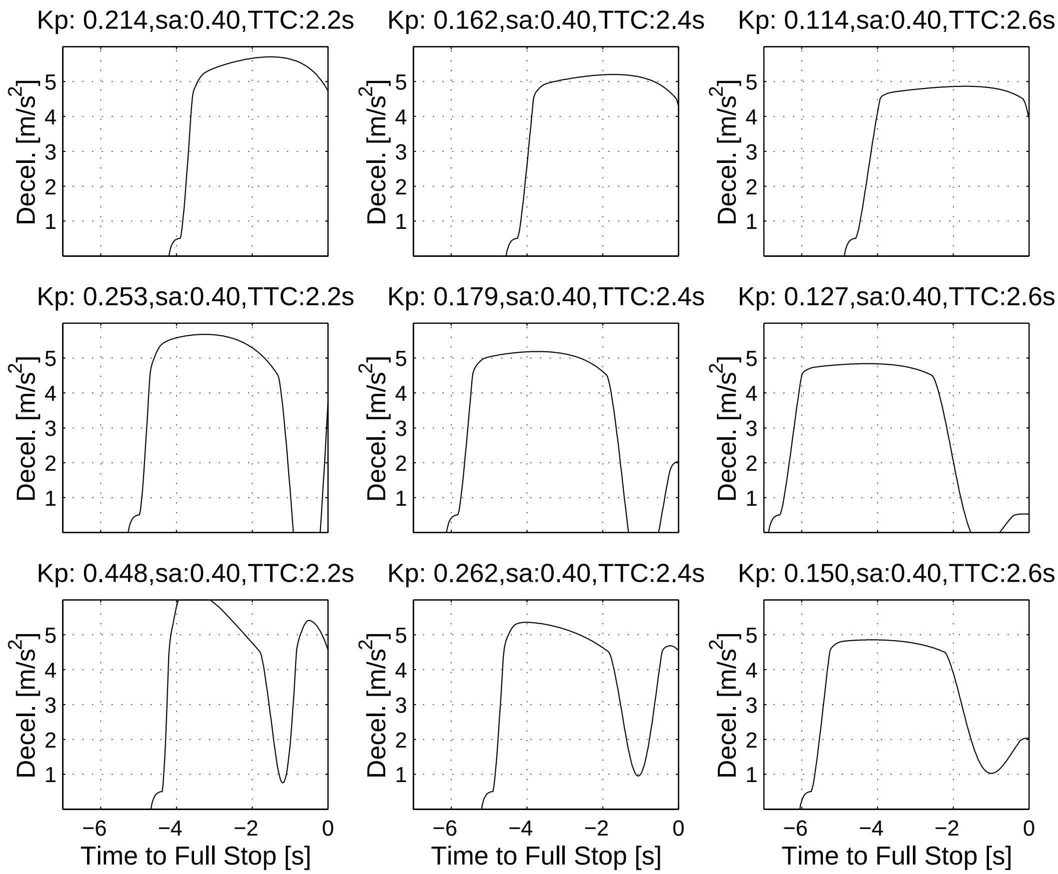

Figure 5. Each panel depicts deceleration profiles for a different onset TTC. Panels in a column share the same onset TTC. Within each column, the control gains were adapted to generate the three classes of characteristics deceleration profiles from Fig. 3. Each group of three panels in a column shows in essence the effect of an increasing control gain on the deceleration profiles.

6.6.4 Individual Differences

The fact that the multi-modal subjects initiate their deceleration earlier can also be explained by assuming that their perceptual bias is less than for the expert drivers. However, we do not accept this explanation until we have collected more data and do no longer see a clear relationship between adopted stopping strategy and DS experience[17]. This hypothesis is none-the-less highly plausible given often reported individual differences in people's: susceptibility to experience vection, tendency to become motion sick, and differential sensitivity between visual and vestibular information. Note however that a clear understanding of the effects that different combination of perceptual scaling factors have on the possible deceleration profiles demands a study like the one presented in this paper.

The observed differences between subjects in the simulator is also not likely to be the result of different preferred control strategies because they all adopt the same strategy in reality (two of the subjects who show multi modal deceleration profiles participated in the instrumented vehicle study described in Boer et al. (2000) where they exhibited constant deceleration profiles during the many stopping maneuvers.

[17] If experienced drivers would adopt a more realistic brake onset TTC (i.e. one that is greater rather than smaller than the one exhibited by the novice drivers), then this could have been evidence for an enhanced perception suggesting that they learned to become more sensitive to the available cues as well as perhaps have picked up cues that they would normally not or only to a vary small degree rely on in reality.

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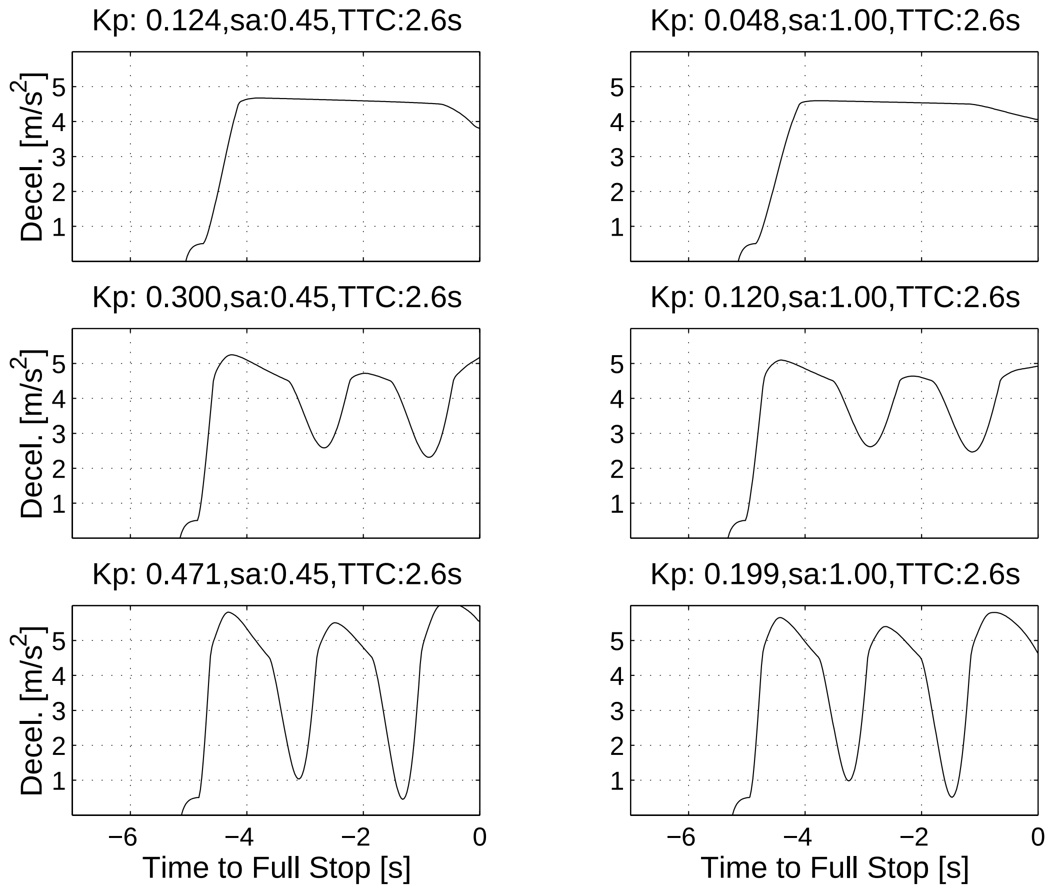

Figure 6. Deceleration profiles obtained when the control gain increases (top to bottom) for reality (right column) where the perceptual scaling is unity for all cues and for a simulator in which the hypothesized crucial perceptual scaling ratio equals 1 (i.e. $s_a = s_v^2 / s_d$). The top row shows what we observed in reality.

7 THE OPTIMAL DRIVING SIMULATOR SCALE FACTOR

The optimal scale factor adopted in a driving simulator is hypothesized to be a function of perceptual biases

> ***Hypothesis:*** *When the square of the perceptual bias in speed divided by the perceptual bias in distance equals the perceptual bias in acceleration that drivers experience in a driving simulator, then they can easily adapt the control strategy they learned in reality and achieve efficient stopping behavior that closely resembles their behavior in reality.*

Next we explain why this is so based on the proposed model. If we assume that drivers indeed base their control on the following error signal,

$$e = \frac{v^2}{2d} - a$$

and that perception of distance, speed, and acceleration are biased (i.e. perceived at a fraction of their true magnitude), then the perceived error becomes

$$e_p = \left(\frac{v_p^2}{2d_p} - a_p \right) = \left(\frac{s_v^2 v^2}{2s_d d} - s_a a \right) = \frac{s_v^2}{s_d} \left(\frac{v^2}{2d} - \frac{s_d s_a}{s_v^2} a \right).$$

From this equation it is clear that the error signal is a simple scaled version of the one perceived in reality when[18]

$$s_d s_a = s_v^2$$

In that case, the only adaptation that the driver needs to employ is an increase in the control gain of a factor s_d / s_v^2 as explained in Section ??. Under these conditions, achieving a constant deceleration strategy is easily obtained by simply increasing the gain. The key is that when $s_d s_a = s_v^2$, that expectations match observations after the gain has been increased. Note that the need for an increased gain is immediately obvious to the driver because the perceived desired acceleration (i.e. $v_p^2 / 2d_p$) is not reached after the vehicle is assumed to have reach steady state. Thus the error signal remains positive. By simply increasing the gain this is immediately remedied. The amount of required gain increase is simply about s_v^2 / s_d (i.e. this additional gain factor equals approximately the expected change in error divided by the observed change in error). If the same gain correction rule is applied when $s_a < s_v^2 / s_d$, then we can see that the adopted gain factor is greater than s_v^2 / s_d thus resulting in a larger gain increase than when the ratio is unity. This is easily seen because the error has not decreased as much as expected because $s_d s_a / s_v^2$ is less than unity. In other words, e_p is positively biased so that it does not decrease as much as they expected thus suggesting the need to increase the control gain. This positive bias is purely perceptual and the truly required adaptation is a decrease in gain rather than an increase. Hence the paradox that hinders rapid adaptation to an efficient deceleration strategy.

Interestingly, if we look at the upper right panel in Fig. 5, we see that the optimal gain for an onset TTC of 2.6 and an s_a of 0.4 (i.e. $s_d s_a / s_v^2 = 0.8 * 0.4 / 0.6^2 = 0.89 < 1.0$) is 0.114, which is less than the optimal control gain of 0.124 when $s_a = 0.45$ and the ratio $s_d s_a / s_v^2$ unity as in the upper left panel in Fig. 6. Herein lies the problem that simulator drivers face. The gain correction rule tells them that they should increase their gain, even though they should in fact decrease their gain to achieve a constant deceleration strategy. This explains why subjects may require so much exposure before they can attain an efficient constant deceleration stopping strategy.

When the perceptual scaling for acceleration is relatively better than for distance and speed (i.e. $s_d s_a / s_v^2 > 1$), then we expect substantially different control strategies. A simple thought experiment reveals that this situation may lead to the gradually increasing deceleration rates sometimes observed in fixed base driving simulators (e.g. Suetomi & Kido, 1995). We did not explore this any further because this situation is rather unlikely, based on cost grounds, as it demands a simulator with a good motion base but simple visuals. In further studies we will explore this condition in detail because it provides a good situation to check the model's predictive power.

8 CONCLUSIONS

In reality, many drivers adopt a constant deceleration rate strategy in full stopping maneuvers, especially when in a slight hurry. Experienced driving simulator drivers adopt a similar strategy. However, they appear to initiate their deceleration onset later than in reality and attain higher deceleration rates than what the same drivers exhibit in reality (Boer et al., 2000). Less experienced driving simulator drivers adopt multi modal deceleration profiles to come to a full stop at a target stop line. Over time, after extensive exposure, simulator drivers appear able to attain expert driver status as demonstrated by their efficient braking strategy (i.e. nearly constant deceleration). However, since this strategy differs from the one they exhibit in reality (i.e. in the simulator drivers initiate braking later and brake harder), the question remains whether this strategy is identical to what they use in reality but simply biased because of perceptual biases or whether they adopt a heuristic that is as efficient as in reality. Note that comfort does not play as big a role in the simulator since acceleratory forces are presented at a fraction of what they are in reality. Some subjects may, however adopt a cautious braking strategy to avoid motion sickness.

[18] Note that this is also exactly the case where the perceived tau-dot still equals $-1/2$ and thus appears to mediate control.

The proposed proportional controller as a model for human stopping behavior is capable of explaining the different deceleration profiles observed in driving simulators for drivers with different levels of experience. The model hinges on the assumption that drivers perceive distance, speed, and acceleration at a scaled, generally scaled down, value. The relative magnitude of these scaling factors causes the model to produce significantly different results than those observed in reality. The model explains why drivers appear to have difficulty adopting an efficient constant deceleration profile in the simulator. This apparent difficulty is hypothesized to be due to the discrepancy between what drivers expect is needed to attain a constant deceleration strategy (i.e. increase gain) and the fact that a decrease in control gain is in fact needed to attain the desired constant deceleration strategy. The only situation when drivers can easily adapt to their preferred deceleration strategy is hypothesized to be when the three perceptual scaling factors satisfy a particular relationship (i.e. $s_d s_a = s_v^2$). Contingent on the degree to which this model holds true under repeated testing and further scrutiny, it appears a waste of resources to develop a high-end motion base without the corresponding visuals and other cues to support it perceptually and vise versa. This appears reasonable because vision is needed for assessing the required deceleration rate and the onset time whereas vestibular information in conjunction with some other less accurate and fast sensory information is needed for monitoring momentary deceleration. In other words, there is no need to improve the distance and speed perception, if this does not result in a closer match between s_a and s_v^2 / s_d .

Naturally, these conclusions apply only to stopping behavior and an improvement in visuals, sound, and kinesthetic stimulation has other positive impacts on the realism of driving behavior. However, this study shows that not all improvements are improvements across the range of other behaviors. As the visuals and other non-motion base cues improve, it is reasonable to believe that TTC will be perceived accurately thus causing drivers to initiate deceleration for a stopping maneuver at the same TTC as in reality. However, if the motion base is not also improved, then this is most likely still fueling multi modal braking. The interaction between these perceptual fidelities and driving behavior needs to be established for a range of simulators to evaluate the full validity of our model. Ideally, these types of analysis should be performed on a single simulator whereby several different fidelity levels can be compared and contrasted.

Satoh et al. (1994) present, in Japanese, a very interesting study in which they increase the scale factor of a 6 DOF JARI driving simulator from 10% to 90% in steps of 20% and investigate driver's subjective impression. It appears that the perception of acceleration and speed improved as the scale factor increased but that drivers' incongruency measure was lowest around about 30% for longitudinal accelerations experienced when driving on the straight road. As mentioned before, this may be due to the fact that tilt coordination was used to represent sustained deceleration and acceleration. At high tilt angles drivers realize that they are tilted. To reach these high tilt angles, drivers may also have been able to sense the rotation because it may not have been possible to keep the rotation rate at a sub-threshold rate. Both of these contribute to a sense of incongruency between perception and expectation. Interestingly, given the date of the paper and the state of the art in visual systems at that time, it is equally plausible that a scale factor of 30% yielded a perceptual scaling ratio ($s_d s_a / s_v^2$) of unity thereby facilitating easy adaptation of driving strategies that one would normally employ in reality. This easy adaptation to familiar strategies may also have decreased the subjects' sense of incongruency.

Given the encouraging results, we plan to launch a grand scale research study to gain insight into means to improve simulators at all levels of fidelity. The goal is to stimulate interest in joint analyses of particular driving maneuvers performed in simulators that span a wide range of fidelities. It is expected that the findings may facilitate improvement of simulators of all levels of fidelity by applying artificial scaling factors to yield a perceptual scaling factor of unity. In some cases, it may be better to degrade fidelity in order to achieve more realistic driving behavior that demands attentional resources that are more similar to those that drivers expend in reality. The key is to gain a fundamental understanding about the perceptual and attentional differences between reality and a wide range of simulators so that the models that describe driver behavior under a wide range of fidelities can be used to better map simulator results to reality.

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