A Characterization of Dynamic Human Braking Behavior with Implications for ACC Design

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Abstract

Skilled driving behavior can be characterized as tracking, control, and regulation of appropriate perceptual cues. Because of environmental complexity, drivers must restrict attention to appropriate perceptual cues and act to cause their vehicle to be in an acceptable perceptual state space. From experiments and supporting literature, we identify time headway and time-to-collision as plausible perceptual cues, and characterize skilled braking behavior as a trajectory through the resulting perceptual state space. This trajectory, which terminates at a desired time headway value and infinite time to collision value, evolves in a smooth counterclockwise direction in the perceptual space spanned by time headway and inverse time to collision. Experimental evidence suggests that if automated braking, such as those required in emerging ACC systems, violates the smooth counterclockwise characteristics of this human-generated perceptual trajectory then human subjects perceive the automated braking as unnatural or uncomfortable. Consequently, to produce comfortable performance ACC designers need to develop controllers that emulate this desired perceptual trajectory.

1 Introduction

Adaptive Cruise Control (ACC) is perhaps the feature of advanced vehicle systems that has been studied most. The reason being is that the technology required for ACC implementation is feasible given the current state of the art, and that the complicated human factors for safe and effective ACC use are being unraveled. With these advances in technology and human factors, many vehicle manufacturers have recently introduced or will soon introduce ACC systems in some automobiles. In this paper, we focus on the dynamic characteristics of safe, comfortable, and predictable braking behavior. This paper is written from a perspective that assumes that ACC systems are primarily intended to safely increase driver comfort without taking the driver completely out of the loop.

One way to evaluate automated systems is to determine how human drivers perform the task, and then characterize such behavior. This approach implicitly identifies the skill-based mental model that governs predictions and evaluations of dynamic braking behavior. An automated system can then be designed that safely implements this behavior within the constraints of available technology. To this end, we characterize safe, comfortable, and acceptable braking dynamics through a series of driver-centered experiments using both tests performed in a driving simulator and on a test-track.

The structure of the resulting characterization constrains the design of control strategies for implementing braking in ACC development. The set of control strategies compatible with a driver's mental model are from the class of perception-based target-following controllers. The first step in designing such controllers is the identification of perceptually feasible states (environmental cues that can be used by humans to make decisions and control a vehicle). The second step is the identification of target states that can be used to generate control [1]. We thus associate skilled driving with both an observed perceptual state and a target perceptual state, and generate control based on these states[1].

2 Problem Description and Notation

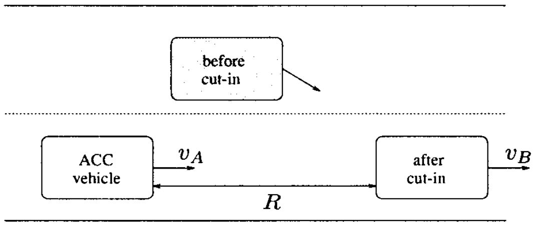

Figure 1: "Cutting in" problem. The cut-in vehicle prior and subsequent to the cut-in event is represented by a shaded box and an open box, respectively.

To determine models of skilled driver behavior, we will focus on the "cutting in" problem wherein vehicle B cuts in front of the driver's vehicle (vehicle A) as diagrammed in Figure 1. Subsequent to a cut-in event, we refer to the cut-in vehicle as the lead vehicle. In the figure, v_A and v_B represent the velocities of the driver's vehicle and the cut-in (lead) vehicle, respectively, $v_R = v_B - v_A$ represents the relative velocity between the vehicles, and R represents the range (relative distance) between the vehicles. From these variables, we con-

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[1] For a designer, emulating these skilled behaviors using controller technology often requires a nonlinear approach.

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struct a state vector $x = [v_A, R, v_R]^T$ that, depending upon the accelerations of vehicles A and B (denoted u_A and u_B, respectively) and assuming disturbance free dynamics, yields a discrete time dynamical system to describe how the state x changes over time (indexed by k) $x_{k+1} = g(x_k, u_A, u_B)$. By convention, $u_A < 0$ indicates that the driver is pressing the brake pedal, and $u_A > 0$ indicates that the driver is pressing the accelerator pedal. The same convention applies for u_B. In this paper, we provide a model of a driver's braking behavior subsequent to their decision to brake. .

Shifting focus from a world centered perspective to a driver centered perspective, we construct a model of car following behavior using a discrete time dynamical state space representation that possesses the following five desirable features:

Feature 1: state variables χ, possibly different from x, are perceivable by driver,

Feature 2: the space spanned by χ (denoted $\mathrm{sp}(\chi)$) equals $\mathrm{sp}(x)$,

Feature 3: an internal dynamical model of perceptual state transitions $\chi(k+1) = \boldsymbol{f}(\chi(k), u_A, u_B)$ can be constructed ($\boldsymbol{f}$ denotes the dynamical response in space χ, and $\boldsymbol{g}$ denotes the related dynamical response in space x),

Feature 4: a control law $u_A = \pi(\boldsymbol{f}, \chi)$ can be constructed from the internal model and the observed perceptual state using cognitively plausible decision mechanisms, and

Feature 5: decision planes can be described in a low dimensional subspace of $\mathrm{sp}(\chi)$ (i.e., decisions depend on relatively few variables).

These five desirable features are motivated by the multiple mental model framework. Clearly, skilled task execution requires perception of cognitively feasible and ecologically informative cues (Features 1-2), and can employ an internal model structure to effect behavior (Features 3-4). Coordination of skilled behaviors (Feature 5) such as the decision to initiate or terminate braking, is tantamount to delimiting behavior domains in perceptual state space, and is addressed further in the two companion papers [2, 3].

In constructing χconsider time headway and inverse time to collision, respectively defined as $T_h = \frac{R}{v_A}$ and $T_c^{-1} = -\left(\frac{v_R}{R}\right)$. These perceptual cues can be directly perceived (Feature 1) by people (see, for example, [5, 6]) and appear to be contributing factors to the initiation of braking [4]. Given these perceptual values, a perceptual state can be defined as $\chi = [T_c^{-1}, T_h, v_A]^T$. Note the one-to-one (except on the surface $v_A = 0$) and onto mapping from the physical state space $x = [R, v_A, v_R]^T$ to the perceptual state space χ whence $\mathrm{sp}(\chi) \approx \mathrm{sp}(x)$ (Feature 2). From an internal model (Feature 3), the driver can form estimates of future perceptual states ($\ell \Delta t$ seconds into the future) yielding predictions $\hat{\chi}(k+\ell)$ which can be used to generate behavior (Feature 4) [4].

3 Experiment I

We have conducted a series of experiments to determine the relationship between braking dynamics and human preferences. In this section, we present the results of the first experiment.

3.1 Experiment Description

In the experiment, two vehicles, denoted vehicle A and vehicle B as in Figure 1, drive on a test track in adjacent lanes. Vehicle B passes vehicle A, slows down, and then cuts into vehicle A's lane at a time that is unknown to vehicle A. During vehicle A's response to this cut-in event, vehicle A records its velocity v_A, its brake pressure (no throttle measurements were recorded), the range R measured with a three beam laser radar, and relative velocity v_R obtained by processing the three range measurements. The experiment was conducted using both a prefatorial automated longitudinal control system as well as an attentive professional driver responding to cut-in events. The data is grouped into three categories: acceptable automated performance, unacceptable automated performance, and professional driver performance without automation, as described in [4]. The behaviors of the automated performance was subjectively classified (by the professional driver) as acceptable/natural or unacceptable/unnatural.

3.2 Results

It is helpful to illustrate the perceptual phase plane trajectories subsequent to the cut-in event for each data class (time histories can be found in [4]). Figures 2-7 display the perceptual trajectory using the sub-state $\chi = [T_c^{-1}, T_h]^T$ for three representative trials. In the perceptual phase plane figures, the trajectories are shown only after a cut-in event (detected by observing a discontinuity in range R); the large diamond indicates the initial perceptual state that results from the cut-in.

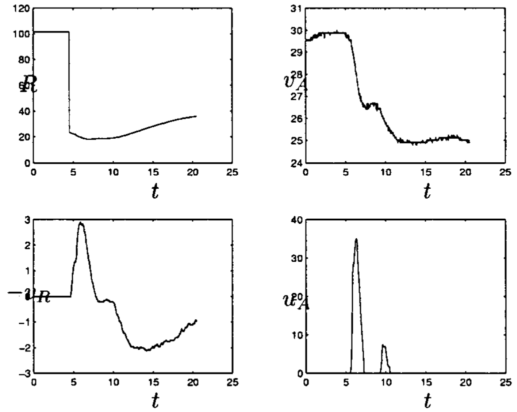

Figure 2: Time histories of `auto_6.prn`. (R in meters, v in meters per second.)

The data is classified into two categories: those for which active braking occurs and those for which no such braking

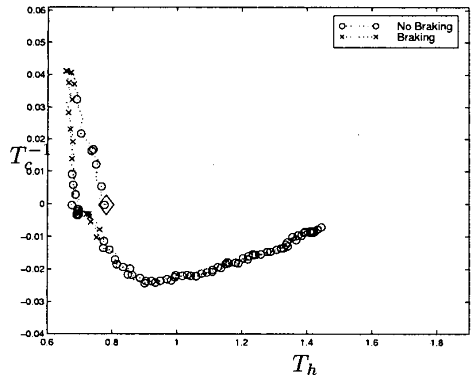

Figure 3: Perceptual phase trajectory of acceptable automated performance `auto_6.prn`**. (T_h in seconds, and T_c^{-1} in inverse seconds.)**

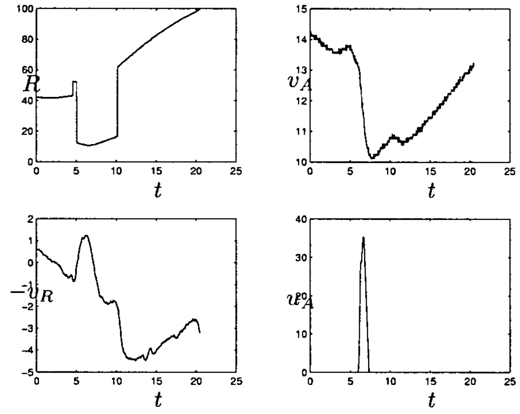

Figure 4: Time histories of `auto_ng.prn`**.**

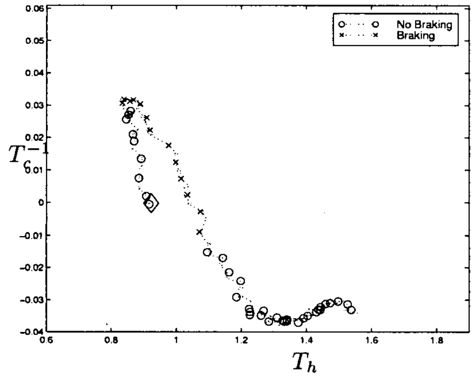

Figure 5: Perceptual phase trajectory of unacceptable automated performance `auto_ng.prn`**.**

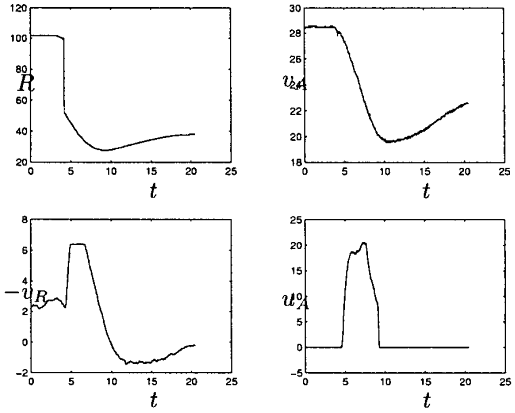

Figure 6: Time histories of `man_0.prn`**.**

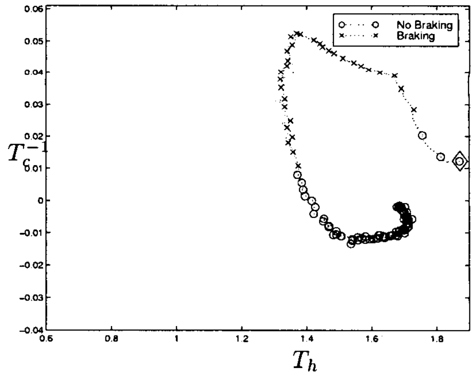

Figure 7: Perceptual phase trajectory of manual performance `man_0.prn`**.**

occurs, indicated in the Figures with a × and a o, respectively. The sequence of o's present after the cut-in event indicate the amount of time taken to react to the cut-in event.

Four observations are apparent:

- The decision to brake is made (ignoring reaction time) when $T_c^{-1} > 0$ ($v_R > 0$). Conversely, a driver is likely to accelerate when $T_c^{-1} < 0$ ($v_R < 0$). Thus, dividing driver behavior into active braking and nominal (not-active) braking produces a division roughly at $T_C^{-1} = 0$ ($v_R = 0$).
- When $T_c^{-1} \leq 0$, the factor determining dynamic driver behavior appears to be related to time headway. This is observable from the driver response in `man_0` wherein the driver first establishes zero relative velocity (an infinite time to collision) and then appears to regulate vehicle speed around the time headway value $T_h^* \approx 1.65$s.
- The characteristics of the phase plane trajectory influence the acceptability of the automated performance. Each trajectory in the set of *acceptable* automated behaviors (`auto_0`-`auto_9`) and the manual behaviors (`man_0`-`man_3`) exhibit a *counterclockwise* movement in the phase plane, but the *unacceptable* automated behavior `auto_ng` exhibits a *clockwise* movement. This is most evident when `auto_ng` (Figure 5) is compared to `auto_6` (Figure 5), since these two have similar initial conditions. The test driver reported that `auto_ng` was unacceptable because the braking action was too extreme given that the relative velocity, though positive, was small in magnitude. This "hard-braking plus low relative velocity" characteristic is manifest as an unacceptable clockwise trajectory in the perceptual phase plane.
- The target perceptual state ($T_h \to T_h^*$ and $T_c^{-1} \to 0$) is approximately speed independent.

These observations support the hypothesis that drivers employ T_c^{-1} and T_h to generate braking response. (The third perceptual state v_A is important for speed regulation, such as driving in low traffic density but is not discussed further in this paper.) Note that this braking behavior has as its goal state infinite time to collision and a desired time headway value. Note that, unlike braking descriptions based on range and range rate measurements, the time-based target state is speed independent and is therefore a more likely perceptual target.

4 Experiment II

To further understand the acceptable dynamics of automobile braking, a second experiment was performed. In this experiment, an elementary ACC controller (PD-type operating on range measurements) was developed and evaluated by drivers. We report the results in this section.

4.1 Description

An elementary PD controller was developed and simulated in various cut-in scenarios. This PD controller operated on the error between estimated range R and desired range $R^* = v_A T_h^*$, where computation of R^* from v_A is a concession to hypothesized technological constraints on estimating v_B. Scenarios that produced braking dynamics that violate the desirable (typical) counterclockwise motion were generated. An instrumented vehicle was then equipped with the controller. From the set of scenarios that violated the characteristic motion in computer simulation, a number of cut-in events were tested in the instrumented vehicle to find further support for this hypothesis. Subjective evaluations of ACC performance were then reported.

4.2 Results

In this section, we analyze the dynamic behavior of the elementary PD controller. Consider the dynamic response

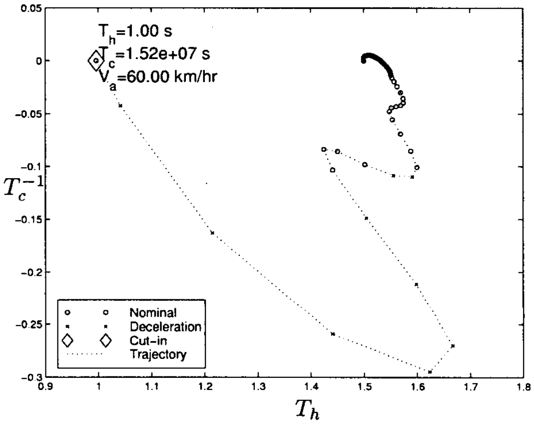

Figure 8: Phase trajectories of controller 1.

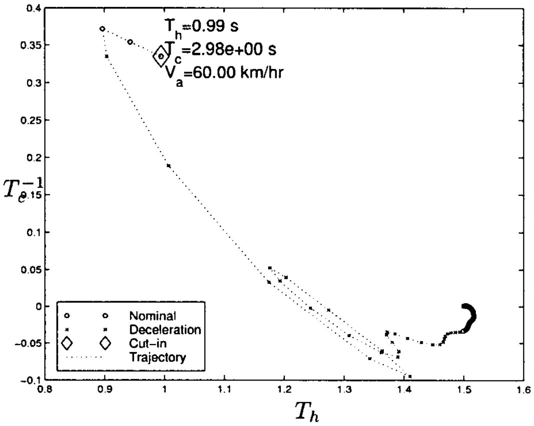

Figure 9: Phase trajectories of controller 1.

shown in Figure 8. These phase plane trajectories represent the automated dynamic response to a cut in event. Before the cut in, the automated controller has established a speed of $v_A \approx 60$ km/hr and a headway of $T_h^* \approx 1.5$ s. A vehicle with constant speed $v_B = 60$ km/hr cuts in at a headway of 1.0 s. We see that the desirable counterclockwise trajectory does not smoothly approach the desired time headway value, but instead has an undesirable bump. A bump in the perceptual trajectory corresponds to undesirable and unnatural deceleration. The perceptual trajectory in Figure 9 again represents the dynamic responses to a cut-in event. Before the cut-in occurs, the automated controller has established a speed of $v_A \approx 60$ km/hr at a headway of $T_h^* \approx 1.5$ s. A vehicle traveling at the constant slower speed $v_B = 40$ km/hr cuts in at a headway of $T_h \approx 1.0$ s. Again, the perceptual trajectory exhibits the bumpy, almost oscillatory, trajectory. Several possible explanations exist for this unacceptable trajectory, but the most likely explanation is that the target range is a function of desired time headway and, consequently, must be speed dependent. This speed dependence produces a time-varying target state that is difficult for the PD controller to track.

To validate these predictions obtained in simulation, the instrumented vehicle was driven on a test-track with cut-in events occurring at conditions similar to those shown in Figures 9-9. The drivers subjectively reported a period of rapid braking. This period was followed by a coasting interval which was then followed by another braking interval. This surge, though moderate, still "felt" unnatural.

To this point, potentially problematic cut-in scenarios have been characterized only as counterclockwise trajectories. The elementary PD controller simulated in this section suggest that in addition to clockwise trajectories, non-smooth perceptual phase plane trajectories may also be problematic. This subjective evidence indicates that perceptual phase plane trajectories should not only be counterclockwise, but should also be smooth.

5 Experiment III

To further bridge the gap between the driving simulator-based results in Experiment I and the test track-based results in Experiment II, a third experiment was conducted to determine the behavior of professional drivers in response to a cut-in event.

5.1 Experiment Description

In the experiment, two vehicles drive in the same lane on a closed test track. The subject drives vehicle A which follows vehicle B. The drivers in vehicles A and B are required to maintain an assigned speed $v_A(0)$ and v_B until a chime rings in vehicle A's car. When the chime rings, the driver of vehicle A is to establish a natural following distance (i.e., drive as if vehicle B had just cut-in to vehicle A's lane) while vehicle B maintains a constant speed. The complete details of this experiment can be found in the companion technical report [4]. Measurements obtained in the experiment include R, v_A, brake pressure β, and throttle opening angle α. These measurements are used to compute time headway and time to collision.

5.2 Results

From the experimental data, two observations are worth noting. First (see Figures 10-11) subjects establish natural following distances by generating smooth counterclockwise trajectories in perceptual space. This supports the observations made in the first two experiments that comfortable and predictable braking behavior is characterized by a smooth counter-clockwise trajectory in perceptual state space.

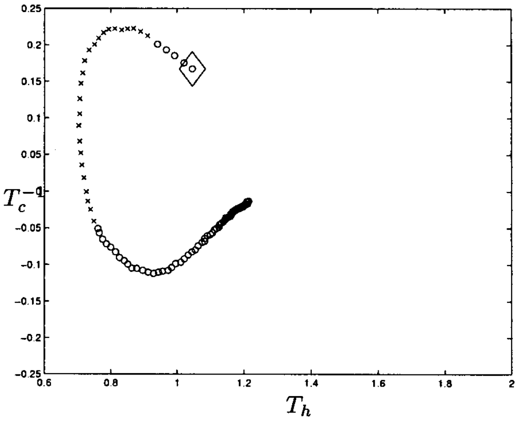

Figure 10: Perceptual phase plane trajectories for subject 1 with initial conditions $(T_h(0), v_R(0)) \approx (1\text{s}, 20\text{km/hr})$.

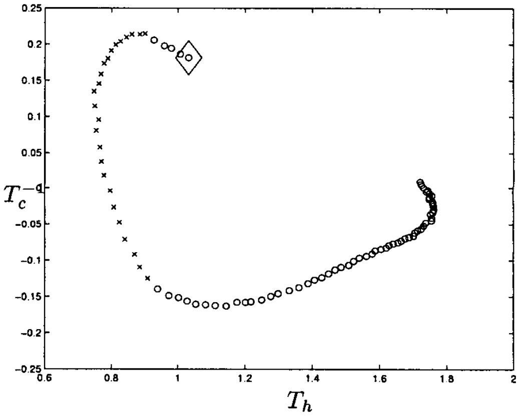

Figure 11: Perceptual phase plane trajectories for subject 2 with initial conditions $(T_h(0), v_R(0)) \approx (1\text{s}, 20\text{km/hr})$.

The second observation worth noting is that (again, see Figures 10-11), subject 1 and subject 2 establish steady-state (i.e., $v_R \approx 0$) behavior at different values of T_h^*. Not only is this true for the initial conditions shown in the figures, but also for every other initial condition. In fact, there is a significant ($P \approx 2 \times 10^{-7}$) T_h^* difference between drivers. For subject A the mean terminal headway is $T_h^* = 1.47$, and for subject B the mean terminal headway is $T_h^* = 2.01$. Interestingly, there are no significant within subject T_h^* differences for different $v_A(0)$ or v_B conditions. Thus, we find evidence that T_h influences braking dynamics independently of v_A.

6 Conclusions and Future Work

Skilled driving behavior can be characterized as the closed loop tracking, control, and regulation of appropriate perceptual cues. Using observations of human braking in response to cut-in events, we have identified time headway T_h and inverse time to collision $T+c^{-1}$ as the relevant perceptual cues for following a lead vehicle. In this perceptual phase space, nominal human braking responses can be characterized by a smooth counterclockwise trajectory terminating at an infinite time to collision (zero inverse time to collision) and a desired time headway value. We hypothesized that when ACC systems that perform active braking emulate human braking behavior the resulting system dynamics are acceptable to human operators. This hypothesis was supported by designing prefatorial ACC systems that violated the characteristic smooth counterclockwise trajectory associated with human braking, and observing that subjective evaluations of such systems were unfavorable; in other words, human subjects did not like ACC systems that did not produce smooth counterclockwise trajectories in perceptual state space. In addition to producing comfortable responses, an ACC system that emulates the braking response generated by a skilled and attentive human driver should allow a driver to form an accurate mental model of the automation and, hence, allow the driver to generate reasonable expectations of ACC performance.

One important aspect of designing ACC systems that achieve predictable, safe, and comfortable dynamics is the design of an appropriate controller. Due to the nonlinear dynamical relationship between driver actions and the perceptual state space (T_h, T_c^{-1}), the design of such a controller can be complex. Among the alternatives for emulating driver behaviors with nonlinear control methods, preliminary work has been done using a model predictive control framework [4]. Investigation of other options including neuro-fuzzy control are currently areas of active research.

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