Automated cars: Queue discharge at signalized intersections with ‘Assured-Clear-Distance-Ahead’ driving strategies

Postprint of:


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Abstract

This study addresses the impacts of automated cars on traffic flow at signalized intersections. We develop and subsequently employ a deterministic simulation model of the kinematics of automated cars at a signalized intersection approach, when proceeding forward from a stationary queue at the beginning of a signal phase. In the discrete-time simulation, each vehicle pursues an operational strategy that is consistent with the ‘Assured Clear Distance Ahead’ criterion: each vehicle limits its speed and spacing from the vehicle ahead of it by its objective of not striking it, regardless of whether or not the future behavior of the vehicle ahead is cooperative. The simulation also incorporates a set of assumptions regarding the values of operational parameters that will govern automated cars’ kinematics in the immediate future, which are sourced from the relevant literature.

We report several findings of note. First, under a set of assumed ‘central’ (i.e. most plausible) parameter values, the time requirement to process a standing queue of ten vehicles is decreased by 25% relative to human driven vehicles. Second, it was found that the standard queue discharge model for human-driven cars does not directly transfer to queue discharge of automated vehicles. Third, a wet roadway surface may result in an increase in capacity at signalized intersections. Fourth, a specific form of vehicle-to-vehicle (V2V) communications that allows all automated vehicles in the stationary queue to begin moving simultaneously at the beginning of a signal phase provides relatively minor increases in capacity in this analysis. Fifth, in recognition of uncertainty regarding the value of each operational parameter, we identify (via scenario analysis, calculation of arc elasticities, and Monte-Carlo methods) the relative sensitivity of overall traffic flow efficiency to the value of each operational parameter.

This study comprises an incremental step towards the broader objective of adapting standard techniques for analyzing traffic operations to account for the capabilities of automated vehicles.

Keywords: Vehicle automation, Microsimulation, Traffic signal, Queue discharge
1. Introduction

A major task facing researchers and practitioners in the transport sector is to establish, as fully as possible, the set of impacts that are likely to occur as road vehicles of various levels of automation (cf. NHTSA, 2013a; SAE International, 2014) become commercially available.

An important mechanism for both direct and indirect impacts will be the changes to the capacity of the road network as it is currently understood (in a human-driver operational regime). Many researchers expect capacity to increase (Anderson et al., 2014; Bhat, 2014; Fagnant and Kockelman, 2014; Mackenzie et al., 2014; Childress et al., 2015), though it has been recognized that this is not a foregone conclusion (Smith, 2012; Wagner et al., 2014; Le Vine et al. 2015). This study focuses on one specific aspect of road network operations: ‘through vehicle’ (i.e. not turning) movements at signalized intersections. The motivation is to provide an evaluation of the queue-discharge characteristics of automated vehicles, both under ‘central’ assumed operational parameters and across a range of combinations of plausible parameter values.

As shown in Section 2, this work extends from previous efforts to establish the impacts of vehicle automation on traffic operations at intersections. In this analysis, the phasing plans of traffic signals are defined to be consistent with current traffic engineering practices (Roess et al., 2010), in which individual traffic streams are sequentially accommodated via visual display of a signal indication. Individual automated vehicles continue (as human drivers do today) to have legal liability for ensuring that they do not strike the preceding vehicle (colloquially termed ‘rear-end crashes’). This study therefore represents an incremental step towards the broader objective of adapting standard techniques for analyzing traffic operations, such as those in the Highway Capacity Manual (TRB, 2010), to account for the capabilities of automated vehicles. This analytical support is required in order to facilitate rational transportation network planning and management for the expected deployment of automated vehicles.
The remainder of this paper is organized as follows. Section 2 describes the body of earlier literature regarding automated vehicles’ operation at intersections. Section 3 outlines the analysis undertaken on this study. Results are presented in Section 4, and Section 5 concludes the paper with a summary of findings and brief discussion of further research needs for the next phase of this line of inquiry.

2. Background

Table 1 summarizes studies that have investigated various possible regimes of automated vehicle operation and their impacts on the capacity of the road network. The literature can be organized along two dimensions. One such dimension is whether the context studied is traffic operations on a freeway (e.g. Kanaris et al., 1997; Vander Werf et al., 2002; Van Arem et al., 2006; Kesting et al., 2008) or at an arterial intersection (Dresner & Stone, 2008; Li et al., 2013; Le Vine et al., 2015). A second dimension, limited to studies that focus on intersection operations, is whether or not the intersection is controlled by traditional signal control (Le Vine et al., 2015). In contrast, virtual traffic lights have also been proposed in which either vehicle-to-vehicle (Ferreira and d’Orey 2012, Sinha et al. 2013) or vehicle-to-infrastructure (Li et al. 2013, Dresner and Stone 2008) communications allow conflicting vehicles to avoid striking one another through dynamic coordination rather than allocation of priority to entire traffic movements by a traditional traffic signal.

<<INSERT TABLE 1 ABOUT HERE>>

The relevance of studying the context of traffic signal operating as they do today is that the first generation of automated vehicles will operate in such an environment.

The logic employed in this simulation (described in Section 3.2) is based on the Basic Speed Rule, which in many jurisdictions requires motorists to travel at a ‘reasonable and prudent’ speed. This obligation is separate and distinct from observing a posted speed limit (NHTSA 2013b). ‘Reasonable and prudent’ vehicle operation is generally interpreted via consistency
with the Assured Clear Distance Ahead (ACDA) criterion (Leibowitz et al. 1998, Maravelias 2015), which requires that a driver operate their vehicle at a sufficiently slow rate of speed that allows them to bring it to a stop "within the distance in which he can plainly see an obstruction or danger ahead" (Berry, 1921, p.175). Likewise, Maravelias (2015, p.204) describes ACDA in the context of objects in the path of a vehicle’s trajectory as: “refer[ring] to the driver’s general responsibility to ensure that the vehicle may stop within the visible line-of-sight frontal range”. The ACDA criterion is the basis of the ‘following too closely’ traffic violation in many jurisdictions (e.g. Section 1129 of the New York State Vehicle and Traffic Code and Section 21703 of the California Vehicle Code). Further, courts have consistently held that “a rear end collision with a stopped vehicle establishes a prima facie case of negligence on the part of the operator of the second vehicle. The rule has been applied [even] when the front vehicle stops suddenly” (quoting Johnson v. Phillips (1999); cf. also Friedman & Malone, 2010). The ACDA criterion of assuming the possibility of unexpected behavior from other vehicles is consistent with the colloquial term ‘defensive driving’, which (ANSI/ASSE 2012, p.7) defines as: “Driving to save lives, time and money, in spite of conditions around you and the actions of others”. With respect to the issue of whether automated vehicles will follow the ACDA criterion (cf. Katrakazas et al. [2016], Milanes and Shladover [2014], and Li et al. [2014] regarding methods for automated vehicle control), it is worth noting that Google’s Self-Driving Car project team asserts non-responsibility for crashes in which its automated vehicles are involved but did not “cause” (Google Inc., 2015).

The possibility of automated vehicles organizing into platoons to increase capacity has been widely discussed (e.g. Kanaris et al., 1997; Vander Werf, 2002; Milakis et al. 2015). Platooning, however, would be compatible with the ACDA criterion only if a following vehicle could have full confidence regarding the future actions of the vehicle ahead of it (i.e. that it would under no circumstances stop short, and that if it therefore did then the following vehicle would not be held liable for the crash). While platooning holds great long-term
promise for improving traffic flow, this study evaluates ACDA-compliant vehicle operations which preclude platooning behavior.

3. Description of simulation analysis

The results reported in Section 4 were generated by a deterministic simulation model of the trajectory of \( n \) queued automated cars at a traffic signal. The traffic stream was specified to be homogenous; the effect of mixed traffic streams is complex and left as an item for future research. All analyses begin with a stationary queue at the moment that the traffic signal provides a ‘green’ indication, and continue until the last vehicle has passed the stopline. The analysis proceeds in discrete time steps of 0.01-second duration.

In the remainder of this section, we first introduce the system’s notation. This is followed by a detailed description of the logic which underpins the operation of the simulation, and then the specification of the operational parameter values employed in the analysis.

3.1 Notation

The following notation (summarized in Table 2) is employed throughout this paper:

\[ \text{Table 2: Notation} \]

- \( \text{veh}_i \): Index of queued vehicles, for \( i = (1 \ldots n) \). Where analyses refer to a generic pair of ‘leading’ and ‘following’ vehicles, the notation \( \text{veh}_i \) and \( \text{veh}_f \) is employed (i.e. \( \text{veh}_f = \text{veh}_{i+1} \)).
- \( H_{\text{min}} \): Minimum headway (in units of time) between the rear bumpers of \( \text{veh}_i \) and \( \text{veh}_f \) that is consistent with the ACDA criterion.
- \( x_{\text{min}} \): Minimum spacing (in units of distance) between the rear bumpers of \( \text{veh}_i \) and \( \text{veh}_f \).
\( x_{\text{veh}} \): Length (units of distance) of vehicles in the simulation. For the sake of exposition, and without loss of generality, it is assumed that all vehicles are passenger cars of the same length (19 feet).

\( x_{\text{intervehicle}} \): Length (units of distance) between the rear bumper of \( v_{\text{eh}} \) and the front bumper of \( v_{\text{hf}} \) when stationary in the queue (prior to beginning forward acceleration).

\( v_{\text{f}}^0 \): Velocity of \( v_{\text{eh}} \) at the point in time that \( v_{\text{eh}} \) may unexpectedly begin emergency braking. In this paper, we evaluate the possibility of \( v_{\text{eh}} \) following an operational strategy in which it selects a maximum ACDA-compliant speed (\( v_{\text{f}}^0 \)) that allows it to be confident that it can avoid a collision with \( v_{\text{eh}} \) (at any time) in the event that \( v_{\text{eh}} \) were to unexpectedly initiate emergency braking.

\( a_f^+ \): Rate of forward acceleration selected by \( v_{\text{eh}} \), which may be based on an a priori assessment of its occupants’ comfort/safety. \( a^+ \) is employed without a subscript in scenarios where it is specified that the rate of forward acceleration is identical for all ten vehicles. This is a simplifying assumption which can, as desired, be readily relaxed. Throughout this paper, all regimes of acceleration (deceleration) are specified to occur at constant rates of acceleration (deceleration), which is consistent with the kinematic analysis employed throughout the Green Book (AASHTO 2011). It would be possible in principle to simulate additional kinematic constraints such as upper bounds on ‘jerk’ (the first derivative of acceleration, which itself is the third derivative of displacement), or any higher-order derivatives of vehicle displacement (the \( n^{th} \) derivative of ‘jerk’). Any such additional constraints would either have no effect (under circumstances where they are not binding) or would ‘worsen’ the simulation’s outputs that characterise network capacity (i.e. calculated capacities would be reduced).

\( a_f^- \): Maximum rate of deceleration of \( v_{\text{eh}} \). Note that any given vehicle can select the value of \( a_f^- \) to which it is willing to subject its occupants in the case of emergency
braking, which may be based on an *a priori* assessment of its occupants comfort/safety. It cannot, however, know the value of $a_i^-$ (the maximum possible rate of deceleration of the vehicle that is ahead of it in the queue).

- $t_{ia,g,f}^+$: Duration of time that elapses after $veh_i$ begins moving and before $veh_f$ begins moving. In the special case of $f = 1$ (the first vehicle in the queue), $t_{ia,g,1}^+$ is equal to the duration of time that elapses after the start of the ‘green’ signal phase and before $veh_1$ begins moving.

- $t_{ia,g,f}^-$: Maximum duration of time that the controller of $veh_f$ is prepared to assume can elapse between $veh_i$ commencing emergency braking and $veh_f$ subsequently initiating emergency braking.

- $x_f$: Distance that $veh_f$ travels during emergency braking (for the duration of braking denoted by $t_f^-$).

- $t_f^-$: Duration of time that $veh_f$ requires to come to rest ($v_f$), conditional on $v_f^o$ (which varies as time proceeds forward during each simulation run) and $a_f^-$ (which is fixed at a pre-specified value for each simulation run).

- $v$: The cruising (maximum) speed of the vehicles in this simulation

A convention employed throughout the paper is that rates of vehicle’s deceleration are described in absolute values, and therefore, the term ‘*maximum rate of deceleration*’ refers to the ‘*maximum absolute value of rate of deceleration*’, and the term ‘*larger rate of deceleration*’ refers to ‘*larger absolute value of rate of deceleration*’.

### 3.2 Simulation logic

The following steps describe the logic employed in the simulation model:

1) Prior to the beginning of the simulation, the system is organized with $n$ vehicles queued at a single-lane intersection approach (in the numerical analysis discussed in Section 4, we analyze values of $n = 10$ and $n = 25$). All vehicles are specified to be
destined to proceed straight through the intersection (i.e. none of the vehicles turn right or left onto the cross street)

2) The event which initiates the simulation ($t = 0$) is the changing of the approach’s signal to a ‘green’ indication.

3) There is then a latency of some duration ($t^+_{lag,1}$), after which $veh_1$ subsequently begins to move forward at a constant rate of acceleration $a^+_1$. $veh_1$ then accelerates at this rate until it reaches its ‘cruising’ speed ($v_{max}$), and then proceeds forward at that speed for the remainder of the simulation.

4) There is then another latency of some duration $t^+_{lag,2}$, after which $veh_2$ subsequently begins to move forward at a constant rate of acceleration $a^+_2$. Note that in Scenario #1 it is assumed that vehicle-to-vehicle (V2V) communications with negligibly-small latency results in $t^+_{lag,f} = 0$ for all vehicles for which $f \geq 2$ (i.e. all vehicles in the queue begin to move forward simultaneously).

5) $veh_2$ then continues accelerating forward at a constant rate of acceleration $a^+_2$ until it reaches a position and velocity where its controller determines that it is traveling at the maximum velocity that will allow it to avoid a crash with $veh_1$ if $veh_1$ were to initiate emergency braking without warning (i.e. the maximum ACDA-compliant velocity). After this occurs, the velocity of $veh_2$ is no longer governed by its maximum desired rate of acceleration ($a^+_2$); from this point forward it can only accelerate during each timestep at a rate that will allow it maintain the required spacing $H_{min}$ (the formula for $H_{min}$ is derived in the Appendix.) to avoid a crash if $veh_1$ begins emergency braking at any time, and if it reaches its cruising velocity ($v_{max}$) it then continues at that velocity. As described in detail in Section 3.3, $veh_2$ cannot know a priori the rate of deceleration that might govern the prospective emergency braking of $veh_1$ or the latency before its ($veh_2$’s) controller initiates its own emergency braking. If the controller of $veh_2$ is pursuing an ACDA-compliant operational strategy, in which it either does not know or does not trust the intentions
of \( veh_1 \), then these assumptions must either be suitably conservative (i.e. err on the side of caution), or the occupant(s) of \( veh_2 \) must accept the possibility of being in a vehicle that could strike the vehicle that it is following and be deemed to be ‘at fault’.

6) Steps #4 and #5 are then repeated for all remaining vehicles in the queue \( (veh_3 \ldots veh_n) \), with references to \( veh_1 \) and \( veh_2 \) in the previous steps replaced with the generic \( veh_l \) and \( veh_f \), respectively.

From the above steps, it can be observed that the simulation does not involve any vehicle actually initiating emergency braking. Instead, each vehicle must operate in a manner that accounts for the possibility of the preceding vehicle commencing an emergency braking maneuver at any point in time with no advance warning. The Appendix of this paper contains a derivation of the minimum headway \( (H_{min} \text{ in units of time}) \) that each following vehicle \( (veh_f) \) must maintain behind the vehicle ahead of it \( (veh_l) \), as a function of the relevant operational parameters.

### 3.3 Selection of operational-parameter values

Table 3 summarizes the specification of parameter values employed in this study; both the specified values and the relevant reference are indicated. For several reasons, it remains “very difficult to select” (quoting Shladover 1997, p.14) unambiguously ‘correct’ operational values of a subset of the parameters that will govern the kinematics of leading and following vehicles. First, system manufacturers generally regard their systems’ sensing, processing, and actuating capabilities as confidential and commercially-sensitive information. Second, these capabilities, were they to be known with certainty, will not be homogeneous for all automated cars; they can be expected to vary between different manufacturers’ systems and in different operating conditions (e.g. good versus poor visibility). Third, in the case of certain parameters (vehicle lengths and current speeds of both the leading and following vehicles), only measurement error separates the measured value from ‘ground truth’. However, two other parameters involve potential future states for which there is no ground
truth that can be known a priori. The two parameters for which the controller of a given \( v_\text{hf} \) must make operational assumptions (because it does not control the actions of \( v_\text{hl} \)) are \( t_{\text{lag,hf}} \) and \( a^- \). A third parameter \( (a^-) \) may share this property, depending on its design, because it may be likely (and certainly is possible) that the designer of an automated-driving algorithm will instruct its vehicle to maintain a vehicle-following headway such that, conditional on assumed values of all other parameters, it would be able to respond to the unexpected initiation of emergency braking by \( v_\text{hl} \) by itself braking at a rate of deceleration \( a^- \) that does not exceed some pre-determined ‘comfortable’ level. A vehicle-controller employing an automated-driving algorithm that follows a protocol of this nature can know a priori the upper bound that its rate of deceleration \( (a^-) \) shall not exceed, whereas a vehicle-controller employing an automated-driving algorithm that is programmed to simply brake as hard as physically possible in an emergency-stop situation cannot know (by definition) the actual rate of deceleration a priori, just as it cannot know the upper bounds of the two other relevant parameters listed earlier in this paragraph that also describe possible future states \( (t_{\text{lag,hf}} \text{and } a^-) \). It is worth pointing out that a maximum permitted rate of deceleration \( (5 \text{ m} / \text{s}^2, \text{which is approximately } 16.4 \text{ ft} / \text{s}^2) \) is specified by the International Standards Organization’s (ISO) Standard #22179, which establishes performance requirements for Full Speed Range Adaptive Cruise Control Systems (ISO 2009). In other words, a vehicle occupant engaging an ISO-#22179-compliant system of longitudinal vehicle-control is electing to forgo the possibility of their vehicle performing automated-braking in excess of \( 16.4 \text{ ft} / \text{s}^2 \) (which is substantially less than the \( 28.3 \text{ ft} / \text{s}^2 \) maximum observed sustained rate of human-driver deceleration reported in [Fambro et al. 1997]), even in the case of an emergency situation where it may be prudent in the interest of crash avoidance or mitigation.
3.4 Description of Scenarios

A Baseline simulation run was first performed, in which all operational parameters were specified to take the ‘central’ values shown in Table 3. In addition, a total of 14 alternative scenarios were undertaken with the following specifications (the second column of Table 3 summarizes the design of the scenarios):

Scenario #1: In this scenario, $t_{lag,f}^+$ is set to zero for $veh_2$ through $veh_n$. This simulates an operational regime in which there is an initial period of latency between the start of the traffic signal’s ‘green’ indication and the beginning of movement of the first queued vehicle ($veh_1$), but in which all queued vehicles behind $veh_1$ begin moving at the same time as $veh_1$.

Scenario #2: The spacing ($x_{intervehicle}$) between the rear bumper of the leading vehicle $veh_l$ and the front bumper of the following vehicle $veh_f$ is specified to be reduced to one foot in this scenario, to test the effect of reducing the distance between stationary vehicles in the queue.

Scenario #3: In this scenario the parameter $a_f^+$ is doubled, to 9.8 ft/sec$^2$ (for $f \geq 2$). This means that all vehicles except $veh_1$ accelerate forward at twice the maximum rate of the ‘central’ value of 4.9 ft/sec$^2$. The motivation of Scenarios #3 through #5 is to identify the effect of varying the forward rate of acceleration of different combinations of vehicle-positions in the queue, where $veh_1$ is a special case in that its forward progress is not constrained by the presence of another vehicle in front of it.

Scenario #4: This scenario is the complement of Scenario #3. Only $veh_1$ is specified to have a maximum rate of forward acceleration ($a_1^+$) of 9.8 ft/sec$^2$.

Scenario #5: This scenario combines Scenarios #3 and #4: all vehicles are specified to have a maximum rate of forward acceleration $a^+$ of 9.8 ft/sec$^2$.

Scenario #6: Only the $a_l^-$ parameter is varied from its ‘central’ value in this scenario; it is specified to take a value of 21.3 ft/sec$^2$. This is equivalent to the maximum observed rate of
deceleration by human drivers in typical passenger cars on wet pavement, as reported by (Fambro et al. 1997), whereas 28.3 ft/sec$^2$ is the rate that Fambro and colleagues report for dry pavement. If the road surface were wet (as opposed to dry), $veh_f$ might plausibly make a less-conservative assumption regarding the maximum rate of deceleration of $veh_l$ and still be ACDA-compliant, because in this situation $veh_l$’s deceleration could not exceed the maximum friction between the wet roadway surface and its tires, which will be smaller for wet pavement conditions. An alternative mechanism to bring about this scenario could be via V2V communications, if $veh_l$ were to communicate to $veh_f$ a pre-commitment not to brake at a rate that exceeds a stated value of $a_l^-$ that is less than $veh_l$’s physical braking capability (possibly in exchange for a monetary micro-payment), regardless of how circumstances may develop. This raises challenges, because for this form of V2V communications to lead to $veh_f$ changing its assumption of the value of $a_l^-$ the implication is that $veh_l$ would be waiving its right to brake at a rate greater than $a_l^-$, even if failing to brake sharply would be to the detriment of its occupants or other physically-proximate people (or property).

**Scenario #7:** In this scenario, $veh_f$ assumes that the maximum possible braking rate ($a_l^-$) of $veh_l$ is 41.6 ft/sec$^2$, compared to the ‘central’ value of 28.3 ft/sec$^2$ that this parameter takes in the baseline scenario (and 21.3 ft/sec$^2$ in Scenario #6). 41.6 ft/sec$^2$ was selected for this scenario as representative of a conservatively-high rate of deceleration, as it is the observed rate of deceleration of two performance sports cars (Chevrolet Corvette and Porsche 911; Motor Trend [2011]) on dry pavement.

**Scenario #8:** $a_f^-$ is set to 28.3 ft/sec$^2$ in this scenario. This implies that the occupants of $veh_f$ accept that their vehicle may brake at a rate up to 28.3 ft/sec$^2$ if the preceding vehicle $veh_l$ initiates unexpected emergency braking (compared to the 16.4 ft/sec$^2$ ‘central’ value)

**Scenario #9:** As with Scenario #8, in this scenario it is the operational parameter $a_f^-$ that is varied from its ‘central’ value. However, this scenario contains a more-conservative
assumption – that the occupants of $veh_f$ will not be subject to deceleration greater than 9.2 ft/sec². This is the maximum rate of deceleration specified in the current generation of Adaptive Cruise Control systems, as characterized by the systems employed in research recently undertaken by Milanes and colleagues (2013).

Scenario #10: In this scenario all vehicles (including $veh_1$) are specified to have a maximum rate of forward acceleration ($a^+$) of 1.9ft/sec². This is representative of the [relatively low] maximum rate of forward acceleration experienced by passengers of High Speed Rail (HSR) systems during normal operation (CA-HSRA, 2004). This scenario builds on earlier work (Le Vine et al. 2015) in which it was suggested that occupants of automated vehicles may seek to minimize their rates of acceleration/deceleration in the interest of making productive or leisurely use of their in-vehicle travel time.

Scenario #11: As in Scenario #10, the rate of forward acceleration is limited to that of HSR (1.9 ft/sec²). In addition, the operational parameter $a_f^-$ is also limited to the maximum typical deceleration rate of HSR, (1.8ft/sec²). This is a more ‘conservative’ set of restrictions than Scenario #10. Whereas forward acceleration is experienced during normal queue discharge operations, this scenario evaluates the consequences of $veh_f$ following a driving strategy that would allow the occupants of $veh_f$ to not be subject to either acceleration or deceleration in excess of the relevant HSR criteria, even in the case of the leading vehicle $veh_1$ initiating unexpected emergency braking.

Scenario #12: In this scenario the parameter $t_{lag,f}$ is specified to be equal to 0.2 seconds, rather than the ‘central’ value of 0.4 seconds. This scenario simulates an operational regime where the controller of $veh_f$ has greater confidence in its ability to react quickly to unexpected emergency braking by $veh_1$. This may plausibly be due to either greater confidence in its ability to sense and process visual information, or to V2V communications concepts such as a leading vehicle transmitting an appropriate message upon initiating emergency braking (cf. Milanes et al. 2011). The issue of ‘trust’ is a major complication with
respect to this specific V2V concept, however. In order for this V2V concept to enable a smaller value of $t_{lag,f}$, a ‘following’ vehicle would need to fully ‘trust’ that the V2V transmission-system of the vehicle ahead of it is in perfect working order, will remain so while these two vehicles are following one another in the traffic stream, and will always provide low-latency and accurate information (i.e. no damage or loss of information packets). Unless there is a paradigm shift in allocating crash-liability away from the currently-prevailing criterion that a vehicle that strikes (‘rear ends’) the vehicle ahead of it is ‘at fault’ for the crash, the logical strategy for the ‘following’ vehicle is to be aware of the V2V signals of vehicles in close proximity, but not to ‘trust’ them to the extent of assuming a value of $t_{lag,f}$ that is smaller than can be accommodated by its own line-of-sight sensors relying on visual information alone.

**Scenario #13:** In this scenario, the length of each vehicle is increased by 25%, from 19 feet to 23.75 feet.

**Scenario #14:** In this scenario, the cruising speed ($v$) of each vehicle is specified to be 63.8 ft/sec (70 km/hour), rather than 45.6 ft/sec (50 km/hour) as in all other scenarios.

4. **Results**

The results presented here consist of outputs from individual runs of the deterministic simulation model for each Scenario, followed by analyses that expose generic relationships between the operational parameter values and output quantities of interest. Where curves are shown in this paper’s Figures, all parameters are specified to take the ‘central’ values shown in Table 3 except where otherwise indicated.

As will be demonstrated below, the ‘saturated flow rate’ concept of ‘capacity’ from the *Highway Capacity Manual* (TRB, 2010) that is calculated as the reciprocal of the [constant] headways beginning with $v_{vehS}$ (i.e. after ‘start-up lost time’ is exhausted by the first four
queued vehicles) does not directly transfer to the automated-vehicle operational regime. Therefore, network efficiency is characterized in the following two ways.

The first of these is the total amount of elapsed time (seconds) between the beginning of the ‘green’ signal indication and when ten queued vehicles progress past the intersection approach’s stopline. In the interest of completeness, and in recognition that the selection of ten as the number of queued vehicles is an arbitrary specification, the calculated time requirement for processing 25 vehicles is also shown in Table 5.

The second is a set of three separate calculated values of ‘flow rate’. The first is calculated by taking the reciprocal of the smallest value of calculated $H_{min}$ between any two pairs of vehicles. The second is calculated by taking the average of headways between $veh_5$ and $veh_{10}$ vehicles in the queue (the first four headways are not included in this calculation of ‘average’ headways in keeping with the treatment in the *Highway Capacity Manual* (TRB 2010) of ‘start-up lost time’ being exhausted after the fourth headway). The third is the calculated hourly flow rate based on the headway between the 5th and 25th queued vehicles (as can be seen below in Figure 5, headways have in general stabilized by the time all 25 queued vehicles in this analysis have been processed).

Except as otherwise indicated the term *efficiency* is employed in the remainder of this section to describe the amount of time required before the 10th queued vehicle passes the intersection approach’s stopline.

Tables 4 and 5 contain the results from the series of scenarios. Our discussion begins with the Baseline scenario, in which all parameters are specified to take ‘central’ values. It can be seen that a total of 15.63 seconds elapse before $veh_{10}$ passes the stopline, and that this is an increase in efficiency (i.e. decrease in time requirement) of 25.4% in comparison to the standard calculation of 20.95 seconds for human drivers (per TRB, 2010). It can also be seen that the headways are not monotonically decreasing, a result which is discussed later in this section. The minimum headway is 1.28 seconds (observed between $veh_5$ and $veh_6$),
beyond which there is an increasing trend (to 1.31 seconds between $veh_9$ and $veh_{10}$, and 1.35 seconds between $veh_{24}$ and $veh_{25}$.

Figure 1 shows the *Time-Space Diagram* of the Baseline scenario; it can be seen that all automated vehicles except the first in the queue are accelerating at their maximum desired rate of acceleration for a relatively small duration of time. By the time the vehicles reach the stopline, all are operating such that their acceleration is constrained by the ACDA requirement to maintain a minimum headway behind the vehicle ahead (with the exception of $veh_1$, which is not following a vehicle and therefore accelerates freely up to its cruising speed). The dashed line in Figure 1 shows the hypothetical trajectory of $veh_2$ if it were not constrained by the ACDA criterion. A time-lapse sequence of selected frames of the Baseline scenario (at $t = 0$ sec, 2.5 sec, 5.0 sec, and 10 sec) can be found in Figure 2.

Scenario #1 demonstrates that an operational regime in which all queued vehicles begin forward movement simultaneously provides little gain in overall efficiency; the reduction is 0.06 seconds (or 0.4%) relative to the Baseline Scenario. The main result from Scenario #1 is shown visually in Figure 3. It can be seen that, while $veh_2$ through $veh_{10}$ do begin moving earlier in Scenario #1, by the time they reach the stopline their forward progress has been constrained by the ACDA criterion such that there is negligible improvement in efficiency. In Table 5, it can be see that this result holds also when considering a queue of 25 vehicles. V2V communications that would allow all queued vehicles to begin moving simultaneously therefore appear to provide little benefit with respect to this measurement of network capacity, conditional on the specified ‘central’ values of all other operational parameters.
This is illustrated further in Figure 4, where it can be seen that impacts on efficiency from marginal reductions (or increases) in this parameter \( t_{lag,f}^+ \) are generally small when evaluating changes from small values of \( t_{lag,f}^+ \), and become large for large values of \( t_{lag,f}^+ \).

The constant spacing between the multiple curves shown in Figure 4 simply shows that increasing \( t_{lag,1}^+ \) has a simple additive impact on the 10th-vehicle-passed-stopline metric.

<<INSERT FIGURE 3 ABOUT HERE>>

<<INSERT FIGURE 4 ABOUT HERE>>

Scenario #2 analyzes the impact of arbitrarily-short distance between queued vehicles while stationary (before any forward movement commences). As with Scenario #1, it can be seen that efficiency increases by a small amount relative to the Baseline Scenario (0.09 seconds, or 0.6%).

The results from Scenario #3 also show little gain in efficiency (0.06 seconds [0.4%]) due to an arbitrarily large increase (a doubling) of the forward acceleration rate of \( veh_2 \) through \( veh_{10} \). However, in Scenarios #4 and #5 the forward acceleration of only \( veh_1 \) and of all vehicles (including \( veh_1 \)) are doubled, respectively. It can be seen that increasing the desired rate of acceleration of only the first queued vehicle leads to a somewhat larger impact on overall efficiency (0.31 seconds [2.0%]) than increasing this rate for only \( veh_2 \) through \( veh_{10} \), and that increasing desired acceleration for all vehicles has a much larger impact (1.9 seconds [12%]).

Scenarios #6 and #7 show that the effects of varying the maximum assumed rate of deceleration of the vehicle ahead of oneself are large. If it is assumed that the leading vehicle will not brake at a rate of acceleration greater than 21.3 ft/sec\(^2\) (which may be a reasonable assumption when the road surface is wet), efficiency is increased by 9.5%. This result is valid providing that the upper limit of deceleration imposed by the wet roadway surface is larger than the maximum desired rate of deceleration of the occupants of \( veh_f \) (i.e.
if \( veh_f \) can be confident that it will be able to brake at its desired rate despite the wet roadway surface); this holds at the ‘central’ value of \( a_f^- \) (16.4 ft/sec\(^2\)), which is the maximum rate of deceleration permitted in ISO-\#22179-compliant systems of longitudinal vehicle control (ISO 2009). Scenario #7 demonstrates that if \( veh_f \) takes a more conservative view of the maximum possible deceleration rate of \( veh_1 \) – 41.6 ft/sec\(^2\), the maximum deceleration rate of performance sports cars (Chevrolet’s Corvette and Porsche’s 911, per Motor Trend, [2011]) – the minimum headway requirements increase and overall efficiency is reduced (by 1.4 seconds or 9.0%).

Scenarios #8 and #9 evaluate the impacts of varying the maximum rate of deceleration to which the occupants of \( veh_f \) are willing to be subjected in case of emergency braking by \( veh_1 \). Large effects were found: an increase to 28.3 ft/sec\(^2\) in Scenario #8 (from the ‘central’ value of 16.4 ft/sec\(^2\)) leads to an 20.0% gain in efficiency (a reduction of 3.12 seconds), and a decrease to 9.2 ft/sec\(^2\) (in Scenario #9) leads to a 27.3% decrease in efficiency (an increase of 4.36 seconds). Scenario #9 is the scenario for which an effect of non-monotonically-decreasing headways can be most clearly observed. As can be seen in Table 4, headways (in units of time) when crossing the stopline decrease from \( veh_1 \) to \( veh_5 \), and then from this minimum value increase monotonically through to \( veh_{10} \). Figure 5 shows that this is true when \( a_f^- = 9.2 \text{ ft/sec}^2 \) (as in Scenario #10), but that the effect varies with different values of \( a_f^- \). As is demonstrated by Equation A12 and shown graphically in Figure 6, increases in travel speed can, under certain combinations of operational parameters, lead to increases in the size of ACDA-compliant headways, when measured in units of time. This is of note as the standard model of human-driver operation (TRB, 2010) when discharging at a signalized intersection approach does not take this phenomenon into account. It is assumed that the inefficiency of ‘start-up lost time’ (which takes a standard value of 2.0 seconds) is exhausted by the time that the first four vehicles have passed the stopline, and that all vehicles starting with \( veh_5 \) proceed through the intersection at the headway that is implied by a constant ‘saturated flow rate’ (which takes a standard value of 1,900 vehicles
per hour in urban areas, implying constant headways of 1.89 seconds). The implication is that a more sophisticated framework for queue-discharge analysis appears to be required to analyze operations of automated vehicles at signalized intersections.

<<INSERT FIGURE 5 ABOUT HERE>>

<<INSERT FIGURE 6 ABOUT HERE>>

Scenarios #10 and 11 analyze the impacts of the hypothetical instruction from automated vehicles' occupants that ride quality (measured as acceleration/deceleration rates) should match HSR, in the interest of occupant comfort and productive use of travel time. Quite divergent effects were found, based on whether it is only forward acceleration (which is experienced in all start-up maneuvers) that is restricted, or if the possibility of deceleration (in the unlikely event of the leading vehicle stopping abruptly) is also introduced as a constraint. In the former case (Scenario #10), efficiency is reduced relative to the Baseline automated vehicle scenario (an increase of 4.87 seconds or 31%), but still represents an improvement relative to human-driven operation (20.50 seconds versus 20.95 seconds for the 10th-vehicle-passed-stopline metric). However, when a restriction to $a_f^{-}$ is also added – meaning that $veh_f$ does not subject its occupants to deceleration in excess of the typical rate of HSR, even in the case of emergency braking by $veh_l$ – efficiency is greatly reduced (a total of 44.37 seconds is required for the 10th-vehicle-passed-stopline metric, which is a 184% increase relative to the automated vehicle Baseline Scenario and a 112% increase relative to human-driven operation).

Scenario #12 shows the effects of the controller of $veh_f$ having increased confidence in its sensing and processing capabilities, such that it is willing to assume that no more than 0.2 seconds could pass (versus the 'central' value of 0.4 seconds) before it begins emergency braking in response to $veh_l$ unexpectedly initiating emergency braking. As discussed in Section 3.4, this could plausibly involve either greater confidence in its ability to process line-of-sight information or in information it would receive via V2V communications from $veh_l$. 
(though there is an issue of ‘trust’ with regards to the latter possibility). We see that overall efficiency from this stimulus is improved by 1.41 seconds (9%).

Scenario #13 investigated the effects of larger vehicles (25% longer than the standard ‘passenger car’ design vehicle (AASHTO 2011). The effect is to increase the time requirement to process a ten-vehicle queue by 1.49 seconds (10%) relative to the Baseline scenario.

Finally, Scenario #14 assessed the impact of an increase in the cruising speed from 45.6 ft/sec (50 km/hour) (as in all previous scenarios) to 63.8 ft/sec (70 km/hour). It can be seen that the impact on overall efficiency is small, with an efficiency gain of 0.13 seconds (0.8%) in the 10th-vehicle-passed-stopline metric.

The scenario-analyses were designed to evaluate the impact on overall system efficiency of non-marginal changes in the operational parameters. Marginal effects (i.e. elasticities) are shown in Figure 7. Arc elasticities were estimated, which we generated by marginally varying the operational parameters. Four estimates of arc elasticity were produced for each parameter by increasing (decreasing) each parameter by 1% (10%), while all other parameters remained fixed at their ‘central’ value. Both 1% and 10% variations were employed, because the discrete-time specification of the simulation implies that small changes (i.e. the 1% perturbations) are more likely than larger perturbations to lead to either under-estimates or over-estimates.

<<INSERT FIGURE 7 ABOUT HERE>>

Figure 7 shows that, conditional on all other parameters taking ‘central’ values, the greatest absolute value of an elasticity is with parameter $x_{veh}$, followed by the parameters $a_f^-$, $a_t^+$, $a_t^-$, and $t_{lag_f}$. As discussed below, these sets of elasticity have different consequences depending on whether the relevant operational parameter is amenable to improvement through technological advance (which is the case with $t_{lag_f}$), or whether it relates to safety
and/or motorists’ comfort/preferences (which is the case with $x_{veh}, a_f^-, a^+, a_i^-$). Figure 8 shows the continuous relationships between each of these three acceleration/deceleration parameters and overall system efficiency. Also shown for comparison purposes are selected values of acceleration that characterize various maneuvers encountered in motorized transportation.

The analysis shown in Figure 7 evaluates the elasticity of system efficiency relative to each individual parameter, conditional on all other parameters taking ‘central’ values. Because we cannot know the values of the operational parameters with certainty, a subsequent analysis was undertaken in order to ascertain more generally the sensitivity of the system to each parameter across a range of plausible parameter-space.

We first specified [plausible but essentially arbitrary] upper and lower bounds for each of the nine operational parameters that were varied, as shown in Table 3. We then performed 10,000 Latin Hypercube draws within this nine-dimensional space, and evaluated the 10th-vehicle-passed-stopline metric for the full sampling space (i.e. each of these 10,000 draws). The smallest and largest obtained values of the 10th-vehicle-passed-stopline metric among the 10,000 runs were 10.53 and 52.40 seconds, and the mean and median were 17.71 and 17.82 seconds, respectively.

The results of this analysis are shown in Figure 9. The numerical values shown at the right-hand-side of the Figure are Pearson’s correlation coefficient values between each of the nine operational parameters and the 10th-vehicle-passed-stopline metric. A relatively large absolute value of a correlation coefficient implies that the relevant parameter has a relatively large impact on the efficiency metric, when evaluated across the entire sampling space. In order to generate the curves plotted in Figure 9, the 10,000 runs were first ordered from lowest to highest per the 10th-vehicle-passed-stopline metric, retaining in this sequencing the values of the operational parameters from each run. The values of the operational
parameters were then plotted, and smoothed with a rolling-average kernel size of 250 to expose general trends. The values of each operational parameter (as well as the output metric) are all normalized within the range zero to one (as shown on the y-axis), to enable all curves to be plotted on the same Figure.

<<INSERT FIGURE 9 ABOUT HERE>>

From Figure 9, it can be seen that \( a_f^- \) (the maximum rate of deceleration to which the occupants of \( veh_f \) may be subject) is identified in this analysis to be the most impactful parameter \((r = -0.51)\) on overall efficiency. In one sense this is unwelcome from the standpoint of automated-vehicle designers, because this value is related to motorists’ preferences and is not amenable to reduction through technological advances. There is also an issue of private versus social welfare: the occupants of \( veh_f \) gain little time by being willing to accept the possibility of a very high rate of deceleration. If \( a_f^- \) takes the value of 28.3 ft/sec\(^2\) instead of the 16.4 ft/sec\(^2\) ‘central’ value (as shown in Scenario #8), the ‘private’ efficiency gains (i.e. the amount of time reduction for \( veh_f \) to pass the stopline) vary from 0.13 seconds (for \( f = 2 \)) to 0.42 seconds (for \( f = 10 \)). These small efficiency gains are generated if only one vehicle chooses to accept the possibility of a very high rate of deceleration. Scenario #8 shows, however, that if all vehicles choose to accept this possibility, the overall gain in efficiency is much larger. In Scenario #8, the tenth vehicle in the queue passes the stopline 3.12 seconds earlier than in the Baseline Scenario, which is an increase in efficiency of 20%. This dichotomy between private and social benefits/costs is characteristic of a collective action problem. Possible solutions exist in principle (e.g. following vehicles might electronically compensate leading vehicles with monetary micropayments in exchange for the leading vehicles committing to small maximum values of \( a_i^- \) (i.e. committing not to brake more sharply than an agreed rate \( a_i^- \), regardless of how circumstances develop), or a central system administrator might dictate that no vehicle is allowed to operate on the basis of a value of \( a_f^- \) that is lower than a pre-defined standardized
value). The latter of these possibilities may well provide larger and more certain efficiency gains, but could prove challenging to implement politically, particularly given that it is directly related to the safety of the occupants of $veh_f$.

Figure 9 also shows that the second- and third-most impactful operational parameters (on overall efficiency) are $t_{lag,f}^-$ ($r = 0.48$) and $t_{lag,f}^+$ ($r = 0.39$). Both of these parameters refer to latency times, either actually experienced during a typical queue discharge (in the case of $t_{lag,f}^+$) or hypothetical in the rare event that the leading vehicle begins emergency braking (in the case of $t_{lag,f}^-$). Therefore, both of these parameters are amenable in principle to technological advances in sensing, processing and actuation that may provide further efficiency gains without compromising either passenger comfort or safety. With regard to $t_{lag,f}^+$ the correlation weakens after approximately the 90th percentile (i.e. there is a reversion to the mean value, meaning essentially no impact at the upper extreme of the distribution). The implication is that in the regions of the sampling space where overall efficiency is very low, whether the value of parameter $t_{lag,f}^+$ is large or small has little impact on the efficiency of the system.

5. Conclusions

In this paper we present findings regarding the efficiency of queue-discharge operations of automated cars at signalized intersections, on the basis of a set of plausible operational strategies and parameters. It comprises an incremental advance towards the wider objective of adapting traffic analysis methodologies to account for automated vehicles.

Though we developed and employed a generally-applicable microsimulation technique which has the capability of testing alternative input-parameter values, we must be clear that the numerical results obtained via this analysis pertain exclusively to the plausible (and grounded in relevant literature), but essentially arbitrary, specifications of parameter values described in this paper. With this caveat in mind, noteworthy findings include:
1) Under ‘central’ assumptions (the Baseline Scenario), the time requirement for ten queued automated vehicles to proceed past the stopline of a signalized intersection approach was found to be 25.4% lower (i.e. more efficient) than the standard calculation for ten human-driven vehicles.

2) Queue-discharge of automated vehicles under the conditions we studied does not, however, follow the principles of the standard model of queue-discharge of human-driven vehicles, which assume monotonically-decreasing headways through the first four vehicles followed by constant headways between all subsequent pairs of vehicles. In the case of automated vehicles, certain sets of input parameter values result in headways initially decreasing to a minimum value, followed by increasing headways for vehicles further back in the queue.

3) It appears plausible that a wet roadway surface may result in increased capacity (and hence decreased congestion) relative to dry conditions, if it allows automated vehicles to make less-conservative assumptions regarding other vehicles’ possible actions but does not constrain their own desired maximum rate of deceleration. This is in contrast to empirical observations of negative capacity impacts when human drivers drive on wet road surfaces (cf. Exhibit 10-15 and 10-16 of TRB, 2010).

4) One specific V2V communications concept – which would allow all queued vehicles to begin forward progress simultaneously after receiving a ‘green’ indication from a traffic signal – provided relatively minor improvements in the traffic-flow efficiency of automated vehicles. Other forms of V2V communications that enable alternative operating regimes may, however, provide larger benefits. For instance, we demonstrate (via Scenario #12) that reducing the assumed maximum latency time between the initiation of emergency braking of a pair of two vehicles that are following one another has a larger impact on overall system efficiency. A reduction in this parameter could plausibly occur either through low-latency V2V communications or technological advances in sensors, processors, and/or actuators. In order for this to be realized via V2V communications, however, there is the issue of whether a
vehicle can have confidence that communications from the vehicle it is following are accurate, trustworthy and complete to some required standard, and whether it is willing to accept legal liability for striking the leading vehicle in the event of a miscommunication. On the part of the leading vehicle, the issue is whether it is willing to accept any liability if it is struck from behind by a following vehicle that was operating on the basis of its V2V communications, or whether it limits its V2V communications to the following vehicle to an advisory-only status (and therefore asserts that liability in the event of a mishap remains strictly with the following vehicle).

5) We demonstrate the relative impact of each operational parameter on overall system efficiency, both via calculation of arc-elasticity values (where all other parameters are fixed at ‘central’ values) and the use of Monte Carlo methods to search across a wider space of combinations of plausible parameter values.

We now conclude this paper with a brief discussion of a set of relevant research issues that either remain open or are raised by this research, and therefore are in need of further enquiry. First, this research was limited to queue-discharge of vehicles proceeding straight through a signalized intersection; an open question remains regarding the gap-acceptance properties of turning vehicles which must filter through conflicting streams of vehicular and/or pedestrian traffic. Second, one technical extension to this analysis that would be of value would be to analyze mixed traffic streams – both mixed in the sense of some human drivers and some automated vehicles and in the sense of vehicles with heterogeneous physical, kinematic, and sensing/processing/actuating characteristics. Another desirable technical extension would be to explicitly account for various dimensions of uncertainty in the sensor-readings of automated vehicles (e.g. uncertainty in a vehicle’s determination of the velocity of the vehicle it is following). Third, a leading vehicle that pre-commits to a following vehicle that it will not under any circumstances brake at a rate beyond some pre-specified limitation can lead to network-capacity gains (see Scenario #6). This concept – a general and legally-
enforceable pre-commitment that one’s vehicle will be constrained by an agreed limit, irrespective of circumstance, rather than the physical limitations of its braking system – introduces novel legal, ethical, and consumer-preference issues that require further study. In general, the issue of moving away from the ACDA-based criterion to alternative criteria that imply different trade-offs between efficiency and crash-risk is a broad topic in need of investigation. Fourth, this study did not account for the possibility of lateral intrusion into the roadway, or of motorists explicitly accepting the risk of selecting a small (non-ACDA-compliant) headway in order to avoid being ‘cut off’ by vehicles in an adjacent lane. Lateral intrusion (e.g. the door of a parked car being opened into the pathway of a moving vehicle, a child ‘darting out’ into the roadway, or a vehicle in an adjacent lane swerving) is widely-present as a possibility on urban streets. Operating a strict ACDA-compliant strategy calculated to avoid rear-end crashes in the event of any possible lateral intrusion would, however, imply arbitrarily slow travel speeds, and human drivers are not required to follow this strategy (cf. Sheppaerd v. Murci, 2003). The question of if, and if so how, automated vehicles will operate to account for the possibility of lateral intrusion into their planned pathway is therefore an important direction for further research. Finally, our view is that the overarching research need within this domain in the mid-term timescale will be to bring together disparate research findings of the type presented in this study, as well as research needs described previously in this listing, into a unified set of standard techniques. The US' Highway Capacity Manual (and similar methodological standards applicable in other countries) will require updating to provide practitioners with standard techniques for general traffic operations analyses with traffic streams that include automated vehicles.

Acknowledgments

The authors wish to thank Steven Shladover for helpful discussions regarding the technical capabilities of automated vehicle sensing and control systems, and three anonymous reviewers for helpful feedback. Le Vine acknowledges financial support of the University Transportation Research Center, Region 2 (Grant # 49997-53-25, titled: Empirical Aspects of
Autonomous Cars). The usual disclaimer applies: any errors in this paper are the authors’ sole responsibility.

References


Appendix: Derivation of minimum headway consistent with an operational strategy compliant with the Assured Clear Distance Ahead (ACDA) criterion

The objective of this derivation is to express $H_{\text{min}}$ as a function of $x_{\text{veh}}$, $t_{\text{lag,fr}}^+, t_{\text{lag,fr}}^-, v_{\text{fr}}^0$, $v_{\text{fr}}^o$, $v_{\text{fr}}^-$, $a_{\text{fr}}^-$, and $a_{\text{fr}}^+$ with each of these terms defined in the system of notation found in Section 3.1. In other words, this derivation identifies the analytical expression that characterizes the minimum headway that is consistent with a following vehicle ($veh_f$) pursuing an ACDA-compliant operational strategy, in the absence of $veh_f$ and $veh_i$ operating cooperatively.

This analysis begins with an assumption on the part of $veh_f$ that $veh_i$ could unexpectedly (and without warning) initiate emergency braking at any time. Prior to the beginning of the possible braking, $veh_i$ and $veh_f$ are traveling at velocities $v_{\text{fr}}^0$ and $v_{\text{fr}}^o$, respectively, with $v_{\text{fr}}^o > v_{\text{fr}}^0$. $veh_f$ must make an assumption regarding the maximum possible rate of deceleration of $veh_i$, denoted as $a_{\text{fr}}^-$. $veh_i$ then decelerates at the constant rate $a_{\text{fr}}^-$ until it comes to a rest ($v_i = 0$). The distance $x_i$ that $veh_i$ travels during emergency braking (for the duration of braking denoted by $t_i$) from velocity $v_{\text{fr}}^0$ to velocity $v_i = 0$ is characterized by the standard kinematic relationship:\

$$x_i = \frac{1}{2} v_{\text{fr}}^0 * t_i \tag{A1}$$

Substituting $\frac{v_{\text{fr}}^0}{a_i}$ for $t_i$ yields:

$$x_i = \frac{1}{2} v_{\text{fr}}^0 * \frac{v_{\text{fr}}^0}{a_i} \tag{A2}$$

which can readily be rearranged to:

$$x_i = \frac{1}{2} \left( \frac{v_{\text{fr}}^0}{a_i} \right)^2 \tag{A3}$$

Once $veh_i$ begins emergency braking, $t_{\text{lag,fr}}$ elapses during which time $veh_f$ continues ‘freely’ traveling at velocity $v_{\text{fr}}^0$. After $t_{\text{lag,fr}}$, $veh_f$ then begins to decelerate at the assumed-to-be-constant rate $a_{\text{fr}}^-$ until it also comes to a rest ($v_f = 0$). The distance traveled by $veh_f$ after $veh_i$ begins emergency braking can be written as:

\[
\text{Braking distance } (x_i) \text{ shown in equation A1 is proportional to the velocity squared } \left( (v_{\text{fr}}^0)^2 \right). \text{ Though not shown explicitly in this equation, this can be obtained if } t_i \text{ (braking time) is expressed as a function of } v_{\text{fr}}^0.
\]

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\[ x_f = v_f^0 * t_{lag,f} + \frac{1}{2} v_f^0 * t_f \]  

(A4)

Substituting \( \frac{v_f^0}{a_f} \) for \( t_f \) yields:

\[ x_f = v_f^0 * t_{lag,f} + \frac{1}{2} v_f^0 * \frac{v_f^0}{a_f} \]  

(A5)

Following re-arranging:

\[ x_f = v_f^0 * t_{lag,f} + \frac{1}{2} \left( \frac{v_f^0}{a_f} \right)^2 \]  

(A6)

An ACDA-compliant operational strategy requires that \( veh_f \) maintain a minimum longitudinal distance \( (x_{min}) \) between \( veh_l \) and itself to avoid a collision in the case of an emergency braking maneuver being initiated by \( veh_l \), which can be written as:

\[ x_{min} = x_f - x_l + x_{veh} \]  

(A7)

with the term \( x_{veh} \) (the length of each vehicle, assumed without loss of generality to be identical for \( veh_l \) and \( veh_f \)) introduced to account for the requirement that the front bumper of \( veh_f \) must not strike the rear bumper of \( veh_l \).

Substituting equations A3 and A6 into A7:

\[ x_{min} = v_f^0 * t_{lag,f} + \frac{1}{2} \left( \frac{v_f^0}{a_f} \right)^2 - \frac{1}{2} \left( \frac{v_l^0}{a_l} \right)^2 + x_{veh} \]  

(A8)

By dividing \( x_{min} \) by \( v_f^0 \), the minimum required headway \( H_{min} \) (in units of time) between \( veh_l \) and \( veh_f \) can be calculated. Therefore, dividing both sides of equation A8 by \( v_f^0 \) yields:

\[ H_{min} = \frac{v_f^0 * t_{lag,f} + \frac{1}{2} \left( \frac{v_f^0}{a_f} \right)^2 - \frac{1}{2} \left( \frac{v_l^0}{a_l} \right)^2 + x_{veh}}{v_f^0} \]  

(A9)

which can be re-arranged to:

\[ H_{min} = t_{lag,f} + \frac{1}{2} \frac{v_f^0}{a_f} + \frac{x_{veh} - \frac{1}{2} \left( \frac{v_l^0}{a_l} \right)^2}{v_f^0} \]  

(A10)

Per the simulation model developed in this study, \( veh_f \) begins to accelerate (at rate \( a_f^- \)) after some duration \( t_{lag,f}^+ \) has elapsed following \( veh_l \) beginning to accelerate (at rate \( a^+ \); this variable carries no subscript here as it is assumed, without loss of generality, that both vehicles accelerate at the same rate). Therefore, during the time period that \( veh_f \) is
accelerating at $a^+$ (i.e. its speed is unconstrained by the presence of $veh_{\text{ahead}}$), $v_f^0$ can be expressed as a function of $v_l^0$ (equation A11), which yields the expression for $H_{min}$ shown in equation A12:

$$v_f^0 = v_l^0 - a^+ \cdot t_{lag,f}$$  \hspace{1cm} (A11)$$

$$H_{min} = t_{lag,f} - \frac{1}{2} \left( \frac{v_l^0 - a^+ \cdot t_{lag,f}}{a_f} \right) + \frac{x_{veh} - \frac{1}{2} (v_f^0)^2}{v_f^0 - a^+ \cdot t_{lag,f}}$$  \hspace{1cm} (A12)$$

From equation A12, it can be seen that whether $H_{min}$ increases or decreases in response to increasing speed (i.e. increases in $v_l^0$) as vehicles accelerate from the initial stopped condition is dependent on the specific values of the empirical parameters. Further, even when the values of all parameters other than $v_l^0$ are fixed, whether $H_{min}$ increases or decreases as speed ($v_l^0$) increases is dependent on the value of $v_l^0$ for certain parameter combinations, such as the combination represented by the non-monotonic curve in Figure 5 for $a_f = 9.2$ ft/sec$^2$. 
Tables and Figures
### Table 1: Summary of previous studies (studies in a freeway context followed by studies in an arterial context) of the impacts of vehicle automation on road network capacity

<table>
<thead>
<tr>
<th>Citation</th>
<th>Context</th>
<th>Vehicle-to-vehicle communications (V2V)?</th>
<th>Vehicle-to-infrastructure communications (V2I)?</th>
<th>Method</th>
<th>Operational regime</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanaris et al. (1997)</td>
<td>Freeway lane with no traffic conflicts (e.g. merging/weaving)</td>
<td>Yes (in a subset of scenarios)</td>
<td>No</td>
<td>Kinematic analysis (synthetic data)</td>
<td>Two-vehicle system (one leading and one following vehicle); the leading vehicle travels at constant 60 miles per hour</td>
<td>Freeway-lane capacity values (vehicles per hour) of up to 7,700 achievable via vehicle-platooning strategies</td>
</tr>
<tr>
<td>Vander Werf et al. (2002)</td>
<td>Multi-lane freeway, including merging and lane-changing behaviour</td>
<td>Yes</td>
<td>No</td>
<td>Kinematic analysis (synthetic data)</td>
<td>Vehicles operate manually (human-driven), under ACC, or under Cooperative Adaptive Cruise Control (CACC)</td>
<td>Impacts of ACC and CACC on capacity of a freeway lane ranged from -19% to +29%</td>
</tr>
<tr>
<td>Van Arem et al., (2006)</td>
<td>Multi-lane freeway with a lane drop</td>
<td>Yes</td>
<td>No</td>
<td>Traffic microsimulation analysis</td>
<td>Vehicles operate manually (human-driven), under ACC, or under Cooperative Adaptive Cruise Control (CACC)</td>
<td>10% increase in capacity with high penetration rates (&gt;60%) of CACC</td>
</tr>
<tr>
<td>Kesting et al. (2008)</td>
<td>Multi-lane freeway, including merging and lane-changing behaviour</td>
<td>Yes</td>
<td>Yes</td>
<td>Bespoke traffic microsimulation analysis (synthetic data augmented with empirical detector data)</td>
<td>Vehicles operate independently under Adaptive Cruise Control (ACC)</td>
<td>25% penetration rate of vehicles operating ACC resulted in elimination of congestion from a bottleneck condition that existed for human-driver operation</td>
</tr>
<tr>
<td>Dresner &amp; Stone (2008)</td>
<td>Arterial intersection</td>
<td>Yes</td>
<td>Yes</td>
<td>Bespoke traffic microsimulation analysis (synthetic data)</td>
<td>An intersection's controller instructs individual approaching vehicles to follow a specific time-space trajectory</td>
<td>Large gains in both capacity and safety (illustrated graphically; numerical values not reported)</td>
</tr>
<tr>
<td>Study</td>
<td>Environment</td>
<td>V2V Options</td>
<td>Traffic Options</td>
<td>分析方法</td>
<td>环境影响</td>
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<tr>
<td>Ferreira &amp; d'Orey (2012)</td>
<td>Arterial street network</td>
<td>Yes</td>
<td>No</td>
<td>Traffic microsimulation analysis (synthetic data)</td>
<td>V2V communications employed to allocate priority to individual vehicles in real-time</td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>Reduction of 1% to 18% in CO₂ emissions, relative to existing traffic signal technology</td>
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<td></td>
<td>Under moderate traffic demands, increases in capacity (relative to a signalized intersection with optimized timing) of 37%, 31% and 32% for left, through, and right-turning movements, respectively. A Capacity reduced when higher traffic-demands were simulated.</td>
<td></td>
</tr>
<tr>
<td>Li et al. (2013)</td>
<td>Arterial intersection</td>
<td>No</td>
<td>Yes</td>
<td>Traffic microsimulation analysis</td>
<td>An intersection’s controller instructs individual approaching vehicles to follow a specific time-space trajectory</td>
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<td></td>
<td>Traditional phasing-based traffic signal control; autonomously-operating car occupants instruct their vehicles to not exceed the acceleration/deceleration limits of rail transit vehicles</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Reduction in capacity of -53% to -4% across various scenarios</td>
<td></td>
</tr>
<tr>
<td>Le Vine et al. (2015)</td>
<td>Arterial intersection</td>
<td>No</td>
<td>No</td>
<td>Traffic microsimulation analysis (synthetic data)</td>
<td>Traditional phasing-based traffic signal control; queue discharge upon beginning of signal phase with ACDA-compliant driving strategies</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>See Section 4</td>
<td></td>
</tr>
<tr>
<td>Present study</td>
<td>Arterial intersection</td>
<td>Yes (in a subset of scenarios)</td>
<td>No</td>
<td>Kinematic analysis (synthetic data)</td>
<td>Traditional phasing-based traffic signal control; queue discharge upon beginning of signal phase with ACDA-compliant driving strategies</td>
<td></td>
</tr>
</tbody>
</table>
### Table 2: Summary of notation

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$veh_i$</td>
<td>Index of queued vehicles, for $i = (1 ... n)$. Where analyses refer to a generic pair of 'leading' and 'following' vehicles, the notation $veh_i$ and $veh_f$ is employed (i.e. $veh_f = veh_{i+1}$)</td>
</tr>
<tr>
<td>$H_{min}$, $x_{min}$</td>
<td>$H_{min}$ is the minimum headway (in units of time) between the rear bumpers of $veh_i$ and $veh_f$ that is consistent with the ACDA criterion. $x_{min}$ is identical, but denotes spacing (units of distance) rather than time</td>
</tr>
<tr>
<td>$x_{veh}$</td>
<td>Length (units of distance) of vehicles</td>
</tr>
<tr>
<td>$x_{intervehicle}$</td>
<td>Length (units of distance) between the rear bumper of $veh_i$ and the front bumper of $veh_f$ when stationary in the queue</td>
</tr>
<tr>
<td>$v_i^*$</td>
<td>Velocity of $veh_i$ at the point in time that $veh_i$ may unexpectedly begin emergency braking.</td>
</tr>
<tr>
<td>$v_f^*$</td>
<td>The maximum ACDA-compliant velocity of $veh_f$</td>
</tr>
<tr>
<td>$a^+$, $a^-$</td>
<td>$a^+$ and $a^-$ denote the maximum rate of forward acceleration and deceleration of vehicles, respectively</td>
</tr>
<tr>
<td>$t_{lag,f}^+$</td>
<td>Duration of time that elapses after $veh_i$ begins moving and before $veh_f$ begins moving</td>
</tr>
<tr>
<td>$t_{lag,f}^-$</td>
<td>Maximum duration of time that the controller of $veh_f$ is prepared to assume can elapse between $veh_i$ commencing emergency braking and $veh_f$ subsequently initiating emergency braking</td>
</tr>
<tr>
<td>$x_f$, $t_f^-$</td>
<td>$x_f$ denotes the distance that $veh_f$ travels during emergency braking; $t_f^-$ denotes the amount of time elapsed during emergency braking</td>
</tr>
<tr>
<td>$v_{max}$</td>
<td>The cruising (maximum) speed of vehicles</td>
</tr>
</tbody>
</table>
Table 3: Central, lower-bound and upper-bound values specified for each operational parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>‘Central’ value (employed throughout, except where otherwise indicated)</th>
<th>Lower bound in Monte Carlo analysis (see Figure 9)</th>
<th>Upper bound in Monte Carlo analysis (see Figure 9)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{veh}$</td>
<td>19 feet</td>
<td>14.25 feet (-25%)</td>
<td>23.75 feet (+25%)</td>
<td>19 feet is the standard length of ‘passenger car’ design vehicle, per (AASHTO, 2011) Obtained by subtracting $x_{veh}$ from the standard ‘front-to-front’ spacing in a stationary queue per (TRB, 2010). This approximates the minimum 2-meter (6.56 feet) ‘front-to-back’ spacing specified by (ISO, 2009) for adaptive cruise control systems</td>
</tr>
<tr>
<td>$x_{intervehicle}$</td>
<td>6 feet</td>
<td>3 feet (-50%)</td>
<td>9 feet (+50%)</td>
<td>4.9 ft/sec² is per (Harwood et al., 1996). 4.3 ft/sec² is implied by Figure 2-24 of (AASHTO, 2011), which describes it as representative of the forward acceleration of ‘a low-performance [human-driven] car’ for the first 100 feet that it travels while accelerating</td>
</tr>
<tr>
<td>$a^+$</td>
<td>4.9 ft/sec²</td>
<td>4.3 ft/sec²</td>
<td>5.5 ft/sec²</td>
<td>Sees discussion in Section 3.3</td>
</tr>
<tr>
<td>$a^-$</td>
<td>16.4 ft/sec²</td>
<td>9.2 ft/sec²</td>
<td>28.3 ft/sec²</td>
<td>Sees discussion in Section 3.3</td>
</tr>
<tr>
<td>$a_{f}$</td>
<td>28.3 ft/sec²</td>
<td>9.2 ft/sec²</td>
<td>41.6 ft/sec²</td>
<td>Assumes 0.1 second for sensing/processing and 0.1 second for actuation of accelerator, per (Kanaris et al., 1997). This same aggregate value of latency time (0.2 seconds) is also employed in (Anderson et al., 2012) Assumes 0.1 second for sensing/processing and 0.1 second for actuation of accelerator, per (Kanaris et al., 1997 and Anderson et al., 2013) Upper bound of the value used in Monte Carlo simulations is set higher than $t_{lag,1}$, due to the more complex task for $veh_2$ and subsequent vehicles (the forward movement of $veh_2$ must be ascertained, in addition to the change of the signal’s indication) See discussion in Section 3.3. Note that low-latency assumptions (e.g. 0.2 seconds) are predicated on ideal conditions of good lighting, fair weather and 0% failure rates in sensing/control (Anderson et al., 2012)</td>
</tr>
<tr>
<td>$t_{lag,1}$</td>
<td>0.2 seconds</td>
<td>0.05 seconds</td>
<td>0.5 seconds</td>
<td></td>
</tr>
<tr>
<td>$t_{lag,f}$ (for $f ≥ 2$)</td>
<td>0.2 seconds</td>
<td>0.05 seconds</td>
<td>1.0 second</td>
<td></td>
</tr>
<tr>
<td>$v_{max}$</td>
<td>45.6 ft/sec</td>
<td>27.3 ft/sec</td>
<td>63.8 ft/sec</td>
<td>30, 50, and 70 km/hour (27.3, 45.6, and 63.8 ft/sec, respectively) are selected as representative cruising speeds of signalized arterials</td>
</tr>
</tbody>
</table>
Table 4: Results (headways between vehicles, in seconds) for the Baseline simulation run and 14 alternative scenarios. Standard values for human drivers (per the Highway Capacity Manual, [TRB 2010]) are shown for comparison.

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Operational parameter that is varied (all other parameters take 'central' values, per Table 3)</th>
<th>Headway elapsed (seconds) before rear bumper of ( v_{eh1} ) passes stopline</th>
<th>Headway elapsed (seconds) between rear bumpers of ( v_{eh1} ) and ( v_{eh2} ) passing stopline</th>
<th>Headway (seconds) between rear bumpers of ( v_{eh3} ) and ( v_{eh4} ) passing stopline</th>
<th>Headway (seconds) between rear bumpers of ( v_{eh5} ) and ( v_{eh6} ) passing stopline</th>
<th>Headway (seconds) between rear bumpers of ( v_{eh7} ) and ( v_{eh8} ) passing stopline</th>
<th>Headway elapsed (seconds) between rear bumpers of ( v_{eh9} ) and ( v_{eh10} ) passing stopline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>All parameters specified with 'central' values (see Table 3)</td>
<td>3.63</td>
<td>1.52</td>
<td>1.38</td>
<td>1.33</td>
<td>1.29</td>
<td>1.28</td>
</tr>
<tr>
<td>1</td>
<td>( t_{lag,f} = 0 ) (for ( f \geq 2 ))</td>
<td>3.63</td>
<td>1.49</td>
<td>1.37</td>
<td>1.32</td>
<td>1.29</td>
<td>1.28</td>
</tr>
<tr>
<td>2</td>
<td>( x_{intervehicle} = 1 ) ft</td>
<td>3.63</td>
<td>1.48</td>
<td>1.37</td>
<td>1.31</td>
<td>1.29</td>
<td>1.28</td>
</tr>
<tr>
<td>3</td>
<td>( a_f^* = 9.8 ) ft/sec^2</td>
<td>3.63</td>
<td>1.48</td>
<td>1.38</td>
<td>1.32</td>
<td>1.29</td>
<td>1.28</td>
</tr>
<tr>
<td>4</td>
<td>( a_f^* = 9.8 ) ft/sec^2</td>
<td>2.62</td>
<td>2.46</td>
<td>1.33</td>
<td>1.27</td>
<td>1.26</td>
<td>1.25</td>
</tr>
<tr>
<td>5</td>
<td>( a_f^* = 21.3 ) ft/sec^2</td>
<td>2.62</td>
<td>1.20</td>
<td>1.14</td>
<td>1.17</td>
<td>1.22</td>
<td>1.25</td>
</tr>
<tr>
<td>6</td>
<td>( a_f^* = 41.6 ) ft/sec^2</td>
<td>3.63</td>
<td>1.46</td>
<td>1.26</td>
<td>1.18</td>
<td>1.12</td>
<td>1.10</td>
</tr>
<tr>
<td>7</td>
<td>( a_f^* = 28.3 ) ft/sec^2</td>
<td>3.63</td>
<td>1.60</td>
<td>1.51</td>
<td>1.47</td>
<td>1.45</td>
<td>1.46</td>
</tr>
<tr>
<td>8</td>
<td>( a_f^* = 9.2 ) ft/sec^2</td>
<td>3.63</td>
<td>1.77</td>
<td>1.74</td>
<td>1.75</td>
<td>1.78</td>
<td>1.81</td>
</tr>
<tr>
<td>9</td>
<td>( a_f^* = 1.9 ) ft/sec^2</td>
<td>5.70</td>
<td>2.21</td>
<td>1.81</td>
<td>1.68</td>
<td>1.61</td>
<td>1.56</td>
</tr>
<tr>
<td>10</td>
<td>( a_f^* = 1.9 ) ft/sec^2, ( a_f^* = 1.9 ) ft/sec^2</td>
<td>5.70</td>
<td>3.71</td>
<td>3.97</td>
<td>4.17</td>
<td>4.29</td>
<td>4.39</td>
</tr>
<tr>
<td>11</td>
<td>( t_{lag,f} = 0.2 ) sec</td>
<td>3.63</td>
<td>1.45</td>
<td>1.24</td>
<td>1.16</td>
<td>1.14</td>
<td>1.12</td>
</tr>
<tr>
<td>12</td>
<td>( x_{veh} = 23.75 ) feet</td>
<td>3.90</td>
<td>1.68</td>
<td>1.51</td>
<td>1.45</td>
<td>1.41</td>
<td>1.42</td>
</tr>
<tr>
<td>13</td>
<td>( v_{max} = 63.8 ) ft/sec</td>
<td>3.63</td>
<td>1.52</td>
<td>1.38</td>
<td>1.33</td>
<td>1.29</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Table 5: Results (elapsed time for \( n \) vehicles to proceed past stopline and implied hourly flow rates) for the Baseline simulation run and 14 alternative scenarios.
<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Total elapsed time (seconds) before rear bumper of veh_{10} passes stopline</th>
<th>Total elapsed time (seconds) before rear bumper of veh_{25} passes stopline</th>
<th>Maximum calculated flow rate (vehicles per hour) implied by the smallest headway between vehicles</th>
<th>Calculated flow rate (vehicles per hour) implied by average headways between veh_{4} and veh_{10}</th>
<th>Calculated flow rate (vehicles per hour) implied by average headways between veh_{4} and veh_{25}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>15.63</td>
<td>35.65</td>
<td>2,813 (between veh_{5} and veh_{6})</td>
<td>2,780</td>
<td>2,720</td>
</tr>
<tr>
<td>1</td>
<td>15.57</td>
<td>35.58</td>
<td>2,813 (between veh_{5} and veh_{6})</td>
<td>2,780</td>
<td>2,721</td>
</tr>
<tr>
<td>2</td>
<td>15.54</td>
<td>35.53</td>
<td>2,813 (between veh_{5} and veh_{6})</td>
<td>2,784</td>
<td>2,725</td>
</tr>
<tr>
<td>3</td>
<td>15.57</td>
<td>35.59</td>
<td>2,813 (between veh_{5} and veh_{6})</td>
<td>2,784</td>
<td>2,721</td>
</tr>
<tr>
<td>4</td>
<td>15.32</td>
<td>35.25</td>
<td>2,880 (between veh_{5} and veh_{6})</td>
<td>2,827</td>
<td>2,742</td>
</tr>
<tr>
<td>5</td>
<td>13.73</td>
<td>33.66</td>
<td>3,158 (between veh_{2} and veh_{3})</td>
<td>2,842</td>
<td>2,746</td>
</tr>
<tr>
<td>6</td>
<td>14.15</td>
<td>31.00</td>
<td>3,303 (between veh_{5} and veh_{6})</td>
<td>3,263</td>
<td>3,221</td>
</tr>
<tr>
<td>7</td>
<td>17.03</td>
<td>39.83</td>
<td>2,483 (between veh_{4} and veh_{5})</td>
<td>2,449</td>
<td>2,391</td>
</tr>
<tr>
<td>8</td>
<td>12.51</td>
<td>24.95</td>
<td>4,390 (between veh_{17} and veh_{18})</td>
<td>4,154</td>
<td>4,286</td>
</tr>
<tr>
<td>9</td>
<td>19.99</td>
<td>49.46</td>
<td>2,069 (between veh_{2} and veh_{3})</td>
<td>1,946</td>
<td>1,863</td>
</tr>
<tr>
<td>10</td>
<td>20.50</td>
<td>41.35</td>
<td>2,627 (between veh_{24} and veh_{25})</td>
<td>2,374</td>
<td>2,524</td>
</tr>
<tr>
<td>11</td>
<td>44.37</td>
<td>115.27</td>
<td>970 (between veh_{1} and veh_{2})</td>
<td>805</td>
<td>774</td>
</tr>
<tr>
<td>12</td>
<td>14.22</td>
<td>31.39</td>
<td>3,243 (between veh_{6} and veh_{7})</td>
<td>3,205</td>
<td>3,162</td>
</tr>
<tr>
<td>13</td>
<td>17.11</td>
<td>39.10</td>
<td>2,553 (between veh_{4} and veh_{5})</td>
<td>2,520</td>
<td>2,474</td>
</tr>
<tr>
<td>14</td>
<td>15.49</td>
<td>34.97</td>
<td>2,857 (between veh_{7} and veh_{8})</td>
<td>2,831</td>
<td>2,789</td>
</tr>
<tr>
<td>Human drivers (per TRB 2010)</td>
<td>20.95</td>
<td>49.37</td>
<td>1,900 (constant after veh_{4})</td>
<td>1,900</td>
<td>1,900</td>
</tr>
</tbody>
</table>
Figure 1: Time-space diagram of autonomous car trajectories following beginning of 'green' signal indication, based on 'central' values of operational parameters
Figure 2: Time-lapse sequence of selected frames of the Baseline scenario (at $t = 0\ sec, 2.5\ sec, 5.0\ sec, \text{ and } 10\ sec$)
Figure 3: Time-space diagram of autonomous car trajectories following beginning of ‘green’ signal indication, showing (dashed curves) the effect of negligibly-low-latency V2V communications that allow all queued vehicles to begin moving simultaneously.
Figure 4: Time requirement for ten vehicles to enter the intersection as a function of elapsed time ($t_{lag,f}$) between successive vehicles ($veh_1$ and $veh_f$) commencing forward acceleration (for $veh_2$ through $veh_{10}$). Curves represent different values of elapsed time before $veh_1$ commences acceleration ($t_{lag,1}$).
Figure 5: Headways between automated vehicles (measured as the elapsed time between the rear bumper of successive vehicles passing the intersection approach’s stopline) for $veh_1$ through $veh_{25}$. Curves represent maximum-permitted values of deceleration for occupants of each vehicle. Heavy grey line shows the curve implied for human drivers.
Figure 6: Minimum headway values consistent with \( veh_f \) operating an ACDA-compliant driving strategy as a function of the speed of \( veh_f \). Curves represent different maximum-permitted values of deceleration (\( a_f \)) to which occupants of \( veh_f \) may be subject.
Figure 7: Estimated arc elasticity of the time requirement (seconds) for ten vehicles to enter the intersection, with respect to each operational parameter.

A: Maximum rate of deceleration of \( v_{\text{veh}} \) during emergency braking (\( a_{\text{E}} \))

B: Maximum rate of forward acceleration (\( a^* \))

C: Cruising speed (\( v_{\text{cru}} \))

D: Intervehicle spacing between rear bumper of \( v_{\text{veh}} \) and front bumper of \( v_{\text{veh}} \) while stationary (\( \Delta\text{DISTANCE}_{\text{NICE}} \))

E: Time elapsed between start of ‘green’ signal indication and beginning of forward acceleration of \( v_{\text{veh}} \) (\( t_{\text{OFF}} \))

F: Assumption made by \( v_{\text{veh}} \) of the maximum deceleration rate of \( v_{\text{veh}} \) during emergency braking (\( a_{\text{E}} \))

G: Vehicle length (\( L_{\text{veh}} \))

H: Assumption made by \( v_{\text{veh}} \) of the maximum duration of time that may elapse after \( v_{\text{veh}} \) begins emergency braking and before \( v_{\text{veh}} \) begins emergency braking (\( t_{\text{OFF}} \))

I: Time elapsed between beginning of acceleration of \( v_{\text{veh}} \) and \( v_{\text{veh}} \) (\( t_{\text{ON}} \))

Elasticity implied by system response to...

- 1% decrease in relevant operational parameter
- 1% increase in relevant operational parameter
- 10% decrease in relevant operational parameter
- 10% increase in relevant operational parameter
Figure 8: Time requirement for ten vehicles to enter the intersection as a function of various maximum rates of acceleration/deceleration ($a^+, a_f^-, a_f^+$).
Figure 9: Curves A-I: Value of each operational-parameter in each of the 10,000 simulation runs, smoothed with a rolling-average kernel size of 250 (to expose general trends). Curve J: Time requirement (seconds) for ten vehicles to enter the intersection in each simulation run, with runs ordered from smallest to largest value.