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Explaining and Preventing Delay at a Bottleneck

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Abstract:	This study tests the feasibility of using a Kalman filter feedback control system at a bottleneck where drivers are forced to merge. Since the bottleneck is assumed to be operating at capacity, traffic delay is expected owing to high traffic density. The roadway geometry, a lane drop where two traffic lanes merge into one, plays a critical role. Individual and group driver behavior is known to cause traffic delay and to be the sole contributor to traffic noise. A driver behavior or stochastic car-following model is developed to study the effects of roadway geometry, traffic density and traffic noise on performance. The model features Brownian motion speed models that mimic driver behavior and simulates real-world bottleneck conditions where drivers start from a standing position, comfortably accelerate to a cruising speed, and then jockey for position when entering the bottleneck. All drivers are assumed to keep a safe headway. Since the model allows individual drivers to adjust their speed according to changing conditions, the model predictions help explain queue formation and performance. The feedback control system, which is assumed to use V2X (vehicle-to-everything) technology, uses an entirely different strategy. It assists drivers: (1) by managing vehicle speed and (2), by arranging vehicles in a ``zipper'' mode formation. A reference signal or tracking function, which proves to be vitally important in arranging vehicles for a ``zipper'' mode, is derived with a non-linear acceleration model. The impacts of deploying this scheme with V2X technology in a ``Smart City'' are discussed.
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EXPLAINING AND PREVENTING DELAY AT A BOTTLENECK

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ABSTRACT

This study tests the feasibility of using a Kalman filter feedback control system at a bottleneck where drivers are forced to merge. Since the bottleneck is assumed to be operating at capacity, traffic delay is expected owing to high traffic density. The roadway geometry, a lane drop where two traffic lanes merge into one, plays a critical role. Individual and group driver behavior is known to cause traffic delay and to be the sole contributor to traffic noise. A driver behavior or stochastic car-following model is developed to study the effects of roadway geometry, traffic density and traffic noise on performance. The model features Brownian motion speed models that mimic driver behavior and simulates real-world bottleneck conditions where drivers start from a standing position, comfortably accelerate to a cruising speed, and then jockey for position when entering the bottleneck. All drivers are assumed to keep a safe headway. Since the model allows individual drivers to adjust their speed according to changing conditions, the model predictions help explain queue formation and performance. The feedback control system, which is assumed to use V2X (vehicle-to-everything) technology, uses an entirely different strategy. It assists drivers: (1) by managing vehicle speed and (2), by arranging vehicles in a “zipper” mode formation. A reference signal or tracking function, which proves to be vitally important in arranging vehicles for a “zipper” mode, is derived with a non-linear acceleration model. The impacts of deploying this scheme with V2X technology in a “Smart City” are discussed.

Keywords: Traffic breakdown, car following, congestion mitigation, Kalman Filter, stochastic processes, stochastic differential equations

INTRODUCTION

A study was conducted and a case was made for using smart technology to prevent traffic delay and improve traffic flow in a "ring road" experiment (Ossenbruggen 2019b). The basic idea is straightforward: provide driver assistance using Kalman Filter feedback control. The study was motivated by a carefully conducted field experiment where traffic breakdown was observed. Drivers of more than twenty passenger cars were instructed to drive at the same *target speed* (Sugiyama et al. 2008). At the start of the experiment, all vehicles were evenly positioned around a single-lane circular roadway. When signaled, the vehicles were observed to move simultaneously at a comfortable acceleration rate. After a few seconds, moving queues were observed and vehicles momentarily stopped, i.e,. traffic breakdown. The author's car following model was developed to simulate these conditions and to develop and test a feedback control system. With it, a traffic breakdown condition can be detected and its speed adjusted in a manner to prevent breakdown.

In this paper, the same approach is used to analyze a "bottleneck." Here, the drivers are forced to merge. Before describing the bottleneck study, we will highlight the key conditions and findings from the previous study. Much was learned from this simple controlled experiment. The conditions were ideal. All drivers were motivated to follow instructions. Distractions, such as, passing vehicles, were eliminated. Only passenger cars were used. Granted, individual reaction times are affected by gender, age, alcohol use, temperament, etc. These factors are considered immaterial given the nature of the experiment.

Four factors explain breakdown in the "ring road" experiment: (1) individual behavior, (2) the behavior of other road users (Ou et al. 2018), (3) traffic density (Mahnke et al. 2005), and (4) traffic volatility (Kish and Bezrukov 2000). Evans (2004) is "overwhelming" convinced that the first two factors determine individual risk associated with traffic safety. One-third of severe car accidents are related to drowsiness (Friedrichs et al. 2010). Since safety is principal concern here, it is reassuring that individual and group behavior was identified as key factors in the "ring road" experiment. Third, the vehicles in the experiment were traveling too close together. By reducing the number of vehicles on the road, i.e., reducing the traffic density, an individual driver could operate a vehicle over a range of speeds without affecting others. By reducing traffic density, vehicle interaction is lessened and the chance of breakdown becomes less likely. Fourth, if the drivers were able to maintain the *target speed*, then the behavior of the other road users and traffic density would have been irrelevant. *Traffic volatility*, measured as the variability in speed that varies over time, is a necessary condition for breakdown. It is also called *traffic noise*, which the author prefers because the latter term implies unwanted.

To explain breakdown at a bottleneck, a fifth factor is added to the above list of items: (5) road geometry or lane drop (Cassidy and Bertini 1999). A bottleneck where two parallel freeway lanes merge into one lane, as shown in Figure 1, is studied. Three zones are shown: *upstream*, *merge* and *downstream.* To explain driver behavior in each zone, mathematical models are developed for each zone and then are linked together to simulate traffic behavior in a case study consisting of twenty vehicles. The vehicles must align themselves and be traveling a speed that allows them to safely proceed to the downstream location at $x(t_3)$.

To achieve a safe merge, drivers must make critical decisions at or before entering the merge zone at location $x(t_2)$. Consider two drivers prior to reaching point $x(t_2)$; one vehicle on the *left-lane* and the other one on the *right-lane.* Their relative positions are important. They are called "side-by-side" and "zipper" merges. Traffic engineers and managers have a strong opinion that a "zipper" merge is more efficient than a "side-by-side" merge (Johnson 2008). The reason is simple. When two vehicles are traveling side-by-side on parallel lanes, one driver must yield to the driver of the other vehicle to avoid a crash. If two vehicles are staggered, then there is no conflict. The author estimates that the majority of drivers prefer to travel side-by-side. Why? It deals with self interest. Simply, an individual wants to minimize travel time and get an advantage "by getting ahead of the next guy." Instinctively, drivers choose the latter option, the "side-by-side" merge.

A Kalman Filter (KF) feedback control system or *Driver-Assistant System* (DAS) has the potential to eliminate this driver instinct and to effectively deal with delay causing factors: roadway geometry, high traffic density, and traffic noise. The acronyms KF and DAS can be used interchangeably. The author chooses to use KF when emphasizing its use as a mathematical tool;

whereas, DAS when emphasizing its potential as a congestion mitigation tool. A two-step strategy is used to demonstrate DAS: (1) Explain delay by simulating it without driver assistance. (2) Prevent delay with a KF feedback control system. A worse case is used. The traffic flow at $x(t_3)$ equals the capacity of a single-lane freeway lane. Performance is evaluated in terms of speed primarily where safety (crash avoidance) acts as a constraint.

The material in this paper is presented step-by-step. The **METHODS** section contains three sections. Each section deals with model building and each has its own focus area. The **Basic Concepts** section focuses on roadway performance and safety. Targets are established and used as benchmarks of success. The **Explaining Traffic Delay** section focuses on driver behavior, drivers who are faced with the task of safely driving through a bottleneck at capacity. A driver behavior or stochastic car-following model is derived and used to describe the obstacles faced by these drivers. The **Preventing Traffic Delay** section focuses on overcoming these obstacles with state space modeling and a Kalman filter. The **DISCUSSION** section focuses on implementing the DAS system in a "Smart City" committed to using ITS technology.

METHODS

A few words about the mathematical notation will help clarify the paper. Drivers must respond to various stimuli at different times; thus location, speed and acceleration are important variables. Driver behavior is described with time-series functions: $x(t), \dot{x}(t)$ and $\ddot{x}(t)$, respectively. Consider the schematic diagram of Figure 1 again and a simulation consisting of twenty vehicles, $n = 20$ vehicles over a time frame of 60 seconds, $0 \leq t \leq 60\ s$. At $t = 0$, $n_{left} = n_{right} = 10$ vehicles. All vehicles start at rest, accelerate, reach a cruise speed, and merge. Thus, $n = n_{left} + n_{right} = 20$ vehicles starting at time $t_3 = 42\ s$. Each driver will enter the merge zone at location $x(t_2)$ at speed $\dot{x}(t_2)$ at time t_2 and enter the downstream zone at location $x(t_3)$ at speed $\dot{x}(t_3)$ at time $t_3 = 42\ s$. Each early arrival driver will spend approximately twelve seconds merging, $t_2 = 30 < t < t_3 = 42\ s$. Late arrivals will spend more time merging when $t_2 < 30\ s$. Early and late arrivals are defined presently.

Basic Concepts

The material given in this section is used throughout the paper. Topics include: *Acceleration*, *Merging Protocols*, *Risk Aversion and Safety* and *Capacity of a Single Freeway Lane*.

Acceleration

A non-linear acceleration model plays a critical role for describing merging behavior:

$$\ddot{x}(t) = a - bt \tag{1}$$

The parameters a and b are the acceleration rate and correction factor, respectively. For $a > 0$ and $b > 0$, the acceleration capability of a vehicle decreases as the speed increases (Elefteriadou 2014). Speed $\dot{x}(t)$ and location $x(t)$ functions are determined by integration.

In the **Explaining Traffic Delay** section, a driver behavior or stochastic car-following model is used to describe a situation where a vehicle decelerates and then accelerates again. This situation typically occurs over time period $t_2 \leq t < t_3$, the *merge zone*, when a following vehicle must change speed to avoid crashing into its lead vehicle. Knowing the speeds, $\dot{x}(t_2)$ and $\dot{x}(t_3)$, and locations $x(t_2)$, and $x(t_3)$, the model parameters of a and b can be determined and speed $\dot{x}(t)$, a quadratic equation, and location $x(t)$, a third-order equation, can be estimated over time $t_2 \leq t < t_3$.

The acceleration model plays equally important roles for describing traffic behavior over time periods $0 \leq t < t_1$, *start-up free-flow traffic zone*. Each vehicle is assumed to comfortably accelerate from a standing position to the *target speed*, u^* at t_1. In this case, the acceleration parameter is equal to $a = u^*/t_1$ and $b = 0$. Here, the vehicle speed $\dot{x}(t)$ and location $x(t)$ equations are linear and quadratic equations, respectively.

There are two cruise zones: $t_1 \leq t < t_2$, *cruise free-flow traffic zone* and $t_3 \leq t < t_4$ *cruise congested traffic zone*. In these cases, the acceleration parameter is equal to $a = b = 0$ with a constant speed equation, $\dot{x}(t)$ and linear location equation $x(t)$.

Merging Protocols

The efficiencies of the "side-by-side" and "zipper" merges can be quantified using the models described in the previous subsection on *Acceleration*. Consider the reactions of any two drivers traveling in parallel upstream lanes who must avoid conflict (crashing) when they reach the bottleneck. Assume when entering the merge zone that they are traveling at same speed at t_2, $\dot{x}_{left}(t_2) = \dot{x}_{right}(t_2) = u^*$.

First consider a "side-by-side" merge where a pair of drivers are assumed to be at the same location, $x_{left}(t_2) = x_{right}(t_2)$ at t_2. At time t_3, however, both vehicles are traveling on the same single-lane roadway where one vehicle is positioned behind the other one. For example, say, $x_{left}(t_3) > x_{right}(t_3)$. The drivers have transitioned from a *free-flow traffic* to a *congested traffic* condition. The vehicle on the left-lane becomes a *leader* and the vehicle on the right-lane becomes a *follower*. Since both drivers want to minimize travel time, both vehicles are assumed to be traveling at the same speed at t_3, such that $\dot{x}_{leader}(t_3) = \dot{x}_{follower}(t_3) = u^*$ and $x_{leader}(t_3) > x_{follower}(t_3)$. Of course, there are inefficiencies in this maneuver. One or both vehicles must change their speeds to achieve this result.

Consider a "zipper" merge where similar assumptions are made but this pair of drivers are assumed to be located at different positions, $x_{left}(t_2) > x_{right}(t_2)$ at t_2. Again, both are traveling at the same speed, $\dot{x}_{left} = \dot{x}_{left} = u^*$. It is not beyond the imagination a merge where neither driver must change speed. In this ideal situation, there is no conflict and no delay. Speed $\dot{x}(t)$ and location $x(t)$ equations are defined by a constant and first-order equations described above.

Risk Aversion and Safety

Regardless of the merge type, all traffic merges are done safely. That means the *gap* between the *lead* and *following* vehicles must be sufficiently wide when the vehicle cross the bottleneck at time t_3. What is a "sufficiently wide gap?" There is no clear-cut answer. It depends on the point of view of the individual being asked. A driver will most likely answer differently than a traffic manager or police officer. There is a delicate balance between the quest for good roadway performance and acceptable risk. The following discussion is an attempt to quantify, codify safety and establish a “safe” gap.

According to the *rule-of-the-road* (ROR) definition advocated in American driving schools, a *safe driving distance* is one car length for each 10 *mph*. For speed u, a “safe” ROR gap is calculated as $ul/10$ where l is a passenger car length. A “safe” gap, now expressed as a *“safe” space headway*, is calculated and denoted as $s_{ROR} = ul/10 + l$, where l is measured in *feet*.

The distance headway at time t_3 is straightforwardly calculated as: $s = s(t_3) = x_{leader}(t_3) - x_{follower}(t_3)$. If $s > s_{ROR}$, then a merge is classified as a “safe, acceptable driver risk" merge; otherwise, it is not.

Capacity of a Single Freeway Lane

To trigger traffic breakdown, a *worse case scenario* is assumed where the bottleneck, a single freeway lane, is assumed to be operating at capacity c. At c, roadway performance is unstable and breakdown is expected. Breakdown is typically associated with a dramatic decrease in speed, queue formation and capacity drop (Castillo 2001) (Cassidy and Bertini 1999).

The Highway Capacity Manual (TRB 2010) guideline lists the capacity as c = 2,380 $v/h/lane$ (*vehicles per hour per lane*) at a traffic density equal to k = 28 *v/km* (45 *v/mile*) and a speed equal to u = 23.7 *m/s* (53.3 *mph*). Given $q = ku$ and $s = 1/k$, capacity relationship is rewritten as $c = u^*/s$. Since s has a different numerical value than s_{ROR}, it is denoted as s_{HCM}. If $s > s_{HCM}$, then a merge is classified as a “safe” merge; otherwise, it is not.

We have two “safe” headway values: s_{HCM} = 36.2 *m* (117 *feet*) and s_{ROR} = 26.9 *m* (82 *feet*), and a discrepancy that is easily resolved. Unstable traffic and breakdown are expected to occur when the traffic flow equals the roadway capacity, which is before a “safe, acceptable driver risk" merge can be achieved. Thus, $s_{HCH} = 36$ *m* takes precedence and is declared the “safe” headway target and is denoted as s_{safe}.

Table 1 contains two sets of information, one set associated with a traffic manager, whose goal is to optimize roadway performance and a set associated with society’s perception of roadway risk and acceptance. It is interesting that neither goal is met. In the case of a traffic manager, when the traffic reaches an optimum, it becomes unstable and delay occurs. In the case of the driving public, drivers, who feel comfortable driving close together, cannot do so because traffic becomes unstable before their "acceptable risk averse" merge can occur.

Explaining Traffic Delay

A principle aim of this paper is to develop a model that simulates reality. The material presented above contains models and assumptions for achieving this aim in a realistic manner. *Traffic noise*, a driver's inability to maintain a target speed u^*, is now addressed.

Stochastic Differential Equations

To stimulate driver behavior, stochastic differential equations (SDE) models are used (Iacus 2008) (Galtier and Touboul 2012) (Weits 1992). The general form of a SDE model is $dX = f(t, X)dt + g(t, X)dW$ where X and W are random variables and where W refers to Brownian motion. For the purposes of simulation, dW is estimated as $W(\Delta T) \sim \sqrt{\Delta T}\sigma N(0, 1)$ with a time step equal to $\Delta t = 0.1\ s$ and σ denoting *traffic noise*. $N(0, 1)$ is a standard normal probability distribution. The introduction of W and σ value are critical in realistically simulating field conditions with a stochastic car-following model and simulation (Kendziorra et al. 2016) (Wagner 2012).

The following models, which were introduced above as deterministic models, are now treated as stochastic differential equations:

$$d\dot{X} = a^* dt + \sigma dW \qquad \text{for } \textit{start-up free-flow traffic}, \ 0 \le t < t_1; \tag{2}$$

$$d\dot{X} = \sigma dW \qquad \text{for } \textit{cruise free-flow traffic}, \ t_1 \le t < t_2; \tag{3}$$

$$d\dot{x} = \big(a - b(t - t_2)\big)dt \qquad \text{for } \textit{merge zone traffic}, \ t_2 \le t \le t_3; \tag{4}$$

$$d\dot{X} = \sigma dW \qquad \text{for } \textit{cruise congested traffic}, \ t_3 \le t < t_4 \tag{5}$$

where a^*, a and b are acceleration rate parameters defined above. Predicted speeds are denoted as $\hat{\dot{x}}(t)$. The estimates of location $\hat{x}(t)$ are estimated using these speed predictions and numerical integration.

The *merge zone traffic* model, a deterministic model, requires clarification. It is invoked only when a driver of a following vehicle violates the safe headway rule, $s < s_{safe}$. When a driver needs to take action, decelerate, the act is deliberate and is assumed to be executed with no traffic noise. At other times when a driver not violate the safe driving rule, traffic noise plays a role. This will be illustrated in the following subsection using different examples.

Car-following

Now, attention turns to describing how vehicles interact with one another and when necessary, a driver will make a correction or corrections. The simplest example deals with the driver of vehicle 1, who is never a driver of a following vehicle, thus this individual is immune from correction. The simulation of this driver uses models (2) and (3) only for time ranges $0 \leq t \leq t_1 = 10$ and $t_1 = 10 \leq t \leq t_2 = 60$, respectively. The initial condition for mmodel (3) is $\dot{X}(t_1) = \hat{\dot{x}}(t_1)$, the last predicted value from model (2). The predicted speeds for $0 \leq t \leq 60$ are used to predict locations $\hat{x}(t)$ for vehicle 1 over this time range.

This scheme is used for vehicles 2 through $n = 20$. Vehicle spacing $s(t)$ for all lead and following pairs is now important. The mathematical notation for a merge is tricky and can divert attention away from obtaining a basic understanding of a bottleneck operating at capacity. To simplify the notation, a *lead* vehicle is denoted as i and a *following* vehicle is denoted as $i + 1$. Vehicle spacing is estimated as $s(t) = \hat{x}_i(t) - \hat{x}_{i+1}(t)$.

Consider a *cruise congested traffic merge* for $t_3 = 42 \leq t < t_4 = 60$ for drivers 1 and 2. Precisely at time $t_3 = 42$ s, the safe headway condition is known with certainty, $s(t_3) \geq s_{safe}$. After this point in time where $t_3 > 42$ s, $s(t)$ can be observed to increase with time or can initially increase and then decrease with time. Suppose in the former case, the headway $s(t)$ is observed to grow over time. It suggests the lead vehicle is speeding up, $\hat{\dot{x}}_i(t) > \hat{\dot{x}}_{i+1}(t)$. The latter case, there are three possibilities: $s(t) < 0$, indicating a crash, $s(t) < s_{safe}$, indicating a safe headway rule violation, and $s(t) \leq s_{safe}$, indicating no violation. When either $s(t) < 0$ or $s(t) < s_{safe}$ is encountered, the car-following model alters the speed and location of the following vehicle:

$$
\begin{aligned}
\hat{\dot{x}}_{i+1}(t) &= \hat{\dot{x}}_i(t) \\
\hat{x}_{i+1}(t) &= \hat{x}_i(t) - s_{safe}
\end{aligned}
\tag{6}
$$

The following speed is set equal to the lead vehicle speed, $\hat{\dot{x}}_{i+1}(t) = \hat{\dot{x}}_i(t)$, and is located a safe distance behind the the lead vehicle.

Model (6) is used to explain the formation of moving and stationary queues for *cruise free-flow traffic* for $t_1 \leq t < t_2$. Even though the traffic on the left and right traffic lanes are classified as free-flow, $s(t) < 0$ or $s(t) < s_{safe}$ violations can be encountered and a driver must make a correction. Model (6) is also used for *cruise congested traffic* for $t_3 \leq t \leq 60$.

When dealing with a stochastic process, surprises occur. It is tacitly assumed above that vehicles will not back up. If $\hat{x}_{i+1}(t) < 0$, then the vehicle is backing up. The situation can occur when *merge zone traffic* model (4) is applied. It is corrected by assuming that a driver will detect the traffic has slowed and will begin decelerating in a timely fashion before time t_2. In other words, a shock wave has formed and a queue is moving in the upstream direction. This impact of this restriction is illustrated in the following section where queue formation is inspected for each of the four merge phases with graphics.

Model Synthesis

Bottleneck breakdown and delay is proving to be a complicated process to analyze as a stochastic process. The use of time-speed $t - \dot{x}$ and time-space $t - x$ trajectories brings clarity. Begin by inspecting Figures 2 through 5 where the $t - \dot{x}$ and $t - x$ trajectories are shown in the upper and lower panels, respectively. Since t_2 and t_3 are important transition times, they are shown. In order to appreciate the importance of each phase of the stochastic car-following algorithm and how they interact, each of these figures are discussed in turn.

Start-up Free-Flow Traffic: The $t - \dot{x}$ trajectories shown in the upper panels of Figure 2 may suggest the drivers are out of control. The reader must be cognizant of the fact that these traces are based on predictions derived from a far from perfect mathematical description of reality. No attempt is made to smooth these trajectories. The simulation uses a time-step of $\Delta t = 0.1$ s giving the impression the drivers are accelerating and braking in quick succession. Looking at these trajectories over the 60 second duration of the experiment show different driver trends where most maintain a constant average speed over time. Significantly, there is a wide range of speeds at $t = 10$

s, suggesting the condition for a successful "zipper" merge is highly unlikely.

The time-space $t - x$ trajectories are smoother than the $t - \dot{x}$ trajectories. Since many of the trajectories cross one another, indicating a crash, suggests that some drivers are reckless. At this point in the discussion, the drivers are acting independently and the constraints discussed above have not been imposed as yet.

Cruise Free-Flow Traffic: Figure 3 shows the $t - \dot{x}$ and $t - x$ trajectories after the restrictions of model (6) are imposed. The drivers are now following one another safely over the entire study period. Over the long term extending past t_2, clusters form. Two form in the left-lane and three form in the right-lane. This is interesting from the point of view that if no bottleneck exists, the drivers would theoretically proceed in this manner.

Merge Zone Traffic: The left panels of Figure 4 show the consequence of superposing the $t - \dot{x}$ and $t - x$ trajectories. The lower panel shows the $t - x$ trajectories crossing. For $0 \leq t < t_2$, this is fine because the drivers are traveling in separate lanes, thus there are no conflicts. For the merge for $t_2 \leq t < t_3$, the situation is more complicated. At t_2, the $t - x$ trajectories may cross, but at t_3, the safe headway rule is enforced. The lower-right panel shows its effect. The upper-right panel with smooth quadratic-shaped $t - \dot{x}$ trajectories show the vehicles being affected. The smooth trajectories and the irregular shaped trajectories extending from $t_2 = 30$ to $t_3 = 42$ s are early arrivals. The smooth trajectories extending from $t = 18$ to $t_3 = 42$ s are late arrivals. The drivers of the late arrivals see a traffic jam forming and begin to comfortably decelerate at time $t = 18$ s.

Cruise Congested Traffic: The lower-right panel of Figure 4 shows large discontinuities between the $t - x$ trajectories at t_3 to draw attention to the impact associated with the steps to mitigate congestion. The discontinuities are removed by generating a new set speed predictions for $t_3 \leq t \leq 60$.

Figure 5 shows the complete simulation run. It shows a few drivers can affect the group and trigger cluster formation. Figure 6 gives a different perspective. Here, the merge is more orderly especially after time t_3 where the drivers operate their vehicles with military precision. Instead of a few drivers affecting the group, two groups of early and late arrivals form. Two vehicles are slowed to a speed approaching zero in comparison to one driver being momentarily slowed to a speed approaching zero in Figure 5 demonstrating how traffic noise σ can affect an outcome.

The average speed, headway and flow at the bottleneck shown in Table 2 for $\sigma/u^* = 0.00$ and 0.03 show neither predictions meet target condition listed in Table 1. A sensitivity analysis puts these predictions of performance in perspective.

Sensitivity Analysis

Before selecting assignment of $\sigma/u^* = 0.03$ or $\sigma = 0.72\,m/s$ for discussion, a sensitivity analysis was performed. Hundreds of simulation runs where the information compiled in tables and figures like Table 2 and Figure 6 were inspected. While an effort to identify a representative Brownian motion value of σ was abandoned, the sensitivity analysis brings insight to the role of traffic noise, i.e., driver behavior.

First, focus on the small values of σ/u^* ratio. At $\sigma/u^* = 0.0$, the stochastic car-following model is transformed into a deterministic model. Regardless of the fact that this model is considered to be poor representation of reality, it clearly shows the roles that high traffic density, measured as a headway, and road geometry affect performance. Since the average flow $\bar{q}(t_3)$ is a function of these two values and $\bar{q}(t_3) < c$, these two factors in combination negatively affect performance.

As the σ/u^* ratio increases leads to a decrease in flow, $\sigma/u^* \uparrow \Rightarrow \bar{q}(t_3) \downarrow$. The decrease is particularly pronounced for $\sigma/u^* \geq 0.03$ where $\bar{q}(t_3) \ll c$. The decline in flow is due to decline in average speed and increase average headway. As the traffic noise increases, average speed decreases and average headway widens as shown in Table 2. Here, the combination of high traffic density, road design and traffic noise - driver behavior - produce a decline in capacity.

In summary, the *stochastic car-following* model or if you prefer a *driver behavior* model, deals with drivers, who wish and act as if free-flow traffic conditions prevailed. According to the model, drivers will act independently until they realize their actions are constrained. When reality finally prevails, the model attempts to mimic the actions of drivers faced with potential crash risk situations.

Preventing Traffic Breakdown

Now, imagine driver assistance, technical assistance, is offered to all drivers entering the bottleneck. The goal is to allow drivers to pass through the bottleneck in "zipper" mode formation. A KF feedback control system, which offers assistance of all $n = 20$ drivers, is contemplated.

A Kalman Filter Model

A KF model is a linear state space model of the following form:

$$\frac{d}{dt}\dot{x} = -\frac{f_d}{m}\dot{x} + \frac{1}{m}f + w_d \tag{7}$$

$$y = \dot{x} + w_d + w_n \tag{8}$$

where the symbol w denotes white noise (MATLAB@9.2 2019). The state equation (7) describes vehicle acceleration $\ddot{x} = d\dot{x}/dt$ as a function of vehicle speed $\dot{x}$, thrust f, drag f_d, and process noise w_d. The measurement equation (8) describes sensor measurement y as the sum of vehicle speed $\dot{x}$, process w_d and measurement w_n noise.

The state equation is derived from Newton's Law, $F = m\ddot{x}$, where the force on the vehicle is $F = f - f_d$ (N), m = vehicle mass (kg) and $\ddot{x}$ = vehicle acceleration (m/s^2). The drag force is estimated as $f_d = \rho C_d A u^*$ where ρ = air density (kg/m^3), C_d = drag coefficient for a passenger vehicle, A = frontal area of the vehicle (m^2) and u^* is the target speed. The drag force f_d is approximately equal to $250N$ for a standard-size American passenger car traveling at $u^* = 23.7$ m/s.

The KF controller is constructed around minimizing process error, $\epsilon = w_r - y$ where w_r denotes a reference signal (Duriez et al. 2017). For this study, w_r is defined to be a tracking function $u^*(t)$ for the time period $0 < t = 60$. The $u^*(t)$ function is distinguishable from the target speed u^*. The tracking function is constructed in a manner to assure that vehicles are aligned properly to achieve a "zipper" merge.

To minimize ϵ, not only does the $w_r = u^*(t)$ function need to be specified but the values of w_d and w_n need to be assigned.

The Tracking Function

To make a convincing argument for feedback control, it is important to appreciate the challenges that drivers face when driving at capacity c. Let's set the stage again. All vehicles start from a standing position, comfortably accelerate and then try to maintain a constant speed. These drivers are assumed to be motivated the same way the drivers in the "ring road" experiment were. They aim to follow instructions but are unable to do so. With feedback control, the operation of the vehicles is taken out of the hands of the drivers and vehicle are controlled by external means for $0 \leq t \leq 60$.

A reference signal w_r is designed to fulfill these drivers' needs by taking advantage of a "zipper" merge. The modeling strategy used here takes advantage of models (2) through (5) assuming $\sigma = 0$ for all these models. In other words, driver behavior as reflected by traffic noise σ - driver behavior - is eliminated from consideration. Thus, the w_r speeds $\dot{x}(t)$ and locations $x(t)$ are derived from deterministic models.

The w_r modeling building effort is straight forward for all merge phases with the exception of the *merge zone traffic*. The left-lane and right-lane vehicles are cruising side-by-side at the same speed u^* and are at the same location $x_{left}(t) = x_{right}(t)$ for times $t > 10$. At time $t_2 = 20$, the controller with the aid of the w_r will instruct the left-lane vehicle to become a leader i and the right-lane vehicle to become a follower $i + 1$. To achieve this positioning, the left-lane vehicle will accelerate and then decelerate and right-lane vehicle will decelerate and then accelerate over the time interval $t_2 = 20 < t < t_3 = 30$. These maneuvers are achieved with the aid of model (4). At t_2, the speeds and locations of the vehicles are:

$$
\begin{aligned}
\dot{x}_i(t_2) &= \dot{x}_{left}(t_2) = u^* \\
x_i(t_2) &= x_{left}(t_2) = x_{right}(t_2) \\
\dot{x}_{i+1}(t_2) &= \dot{x}_{right}(t_2) = u^* \\
x_i(t_2) &= x_{right}(t_2) = x_{left}(t_2) \qquad (9)
\end{aligned}
$$

At t_3, they are:

$$\begin{aligned}
\dot{x}_i(t_3) &= u^* \\
x_i(t_3) &= x_i(t_2) + u^*(t_3 - t_2) + \frac{s_{safe}}{2} \qquad \text{on } \textit{left-lane} \\
\dot{x}_{i+1}(t_3) &= u^* \\
x_{i+1}(t_3) &= x_{i+1}(t_2) + u^*(t_3 - t_2) - \frac{s_{safe}}{2} \qquad \text{on } \textit{right-lane}
\end{aligned} \tag{10}$$

The w_r reference signal for a vehicle traveling on a left-lane is shown by the broken line of the upper panel of Figure 7. Note that the horizontal axis uses the sample κ for plotting and the t_2 and t_3 refer to sample numbers corresponding to clock times 30 and 42 s, respectively.

Model Calibration

As stated above in the *Kalman Filter Model* subsection, the reference signal w_r, traffic noise w_d and measurement noise w_n must be specified. The following rationale is to used make these assignments.

Since traffic noise σ is a reflection of a driver's inability to follow instructions and the sensitivity analysis results given in Table 2 indicate a poor level of performance at $\sigma = 0.72\ m/s$, it seemed appropriate to assign it to w_d.

Since speed measurement data are assumed to be collected on-board the vehicle, transmitted to a central controller, analyzed and transmitted back to the vehicle, it seemed appropriate to make a conservative assignment of measurement noise. $w_n = \sigma = 0.72\ m/s$ was chosen. The measurement noise of equation (8) is a the sum, $w_d + w_n = 1.42\ m/s$.

Model Performance

The KF controller delivers three responses: *true*, $y(t)$; *filtered* $y_F(t)$ and *measured*, $y_M(t)$. The $t - \dot{x}$ trajectories of $y_F(t)$ and $y_M(t)$, shown in the upper panel of Figure 7, track w_r well. The trajectory is delayed but it is of no concern. More importantly, the bottom panel shows the effectiveness of the filter in dealing with noise w_d and w_n, $\epsilon_F(t) < \epsilon_M(t)$.

To test the reliability of the controller, fifty simulations were run. The average values and standard deviations of $y(t)$, $y_F(t)$ and $y_M(t)$ are given in Table 3. The $\bar{u}(t_3)$ predictions are precise and inaccurate, they fail to match the target speed, $u^* = 23.7\ m/s$. For reasons of safety, speed precision is critically important because precisely located vehicles of $\hat{x}(t)$ offers assurance the safe headway rule, $s(t) < s = s_{safe}/2 = 18.1\ m$ is not violated. The speed $t - \dot{x}$ and location $t - x$ trajectories of Figure 8 show $n = 20$ vehicles that start "side-by-side" are rearranged in a "zipper" merge formation prior to reaching the *merge zone* and proceed through the bottleneck with precision.

The feedback control system has two basic aims: to track w_r and to minimize the process w_d and measurement noise w_n. The obstacles associated roadway geometry, operating at roadway capacity, and driver behavior are theoretically overcome with this technique. The benefits are clear. Its performance can be declared optimum. Since the predictions are precise, it suggests the vehicles will proceed through the bottleneck "safely."

DISCUSSION

The author used care in calling DAS a "Driver Assistant System." DAS is considered to be in the same class as ACC, an adaptive cruise control system where V2V (vehicle-to-vehicle) wireless communication is used. In a sense, DAS is similar to the operation of an autonomous vehicle, a self-driving car where the vehicle is capable of sensing the environment with no human input. But unlike an autonomous vehicle, a driver of a DAS vehicle, classified as a Level 1 autonomous car, must steer the vehicle and most importantly, remain alert for reasons of safety. The Green Book (AASHTO 2011) stopping sight distance is calculated to be 152 m or 500 ft with a 2.5 second driver reaction time. The merge length is assumed to be over 280 m or 930 ft, therefore a driver, it can be argued, has ample space to perceive a dangerous situation and respond.

To implement DAS at a bottleneck, real-time vehicle location and speed data are needed. These data can be collected and shared using ITS Cellular-V2X (vehicle-to-everything) communication. For DAS, V2V and V2N (vehicle-to-network) communication are needed where vehicle control instructions and data will be shared using V2N wireless communication.

While Cellular-V2X technology is not fully implemented, no proof of concept can be offered with road testing. According to 5GAA, a partnership of automobile manufacturers and communication companies, steady progress is being made (5G Automotive Association 2018). Success with radar, GPS, Lidar, tire, light sensors and video sensors using Kalman filtering has been reported in the literature. These papers have one thing in common. They track one vehicle. There are exceptions. Ponsa et al. (2005), Luling et al. (2009), Nemati and Astrand (2014), Mathew and Asari (2013) and Yuan et al. (2015) have tracked people and vehicles. In the interim, prototype testing can be pursued where DAS is operated under different weather conditions, times of the day, etc.

DAS meets the requirements of a "Smart City" mobility device. It is aimed at (1) creating less congestion by using cutting edge ITS technology and (2) improving infrastructure by wisely managing traffic data. The "Smart City" concept, which take advantage of improvements in technology for improving lives, has been endorsed by large companies, start-up companies, banks, university-city partnerships (Network Metrolab 2019), the federal government (U.S. Department of Transportation 2019) and the (American Society of Civil Engineering 2019).

Public perception is important. Critics may claim that traveling in a DAS vehicle through a bottleneck with a precisely controlled speed of u^* and headway of $s = 18.1\ m$, is not "safe." $s < s_{ROR} = 26.9\ m$. Public opinion polls indicate that the majority of people would not travel in a Level 5 autonomous car. Convincing the critics that a DAS vehicle is a Level 1 autonomous car will be a difficult task. It uses the same technology as an autonomous vehicle. Finally, there is issue of false security. Hand-held phone use is risky and illegal. Research has shown that "handsfree" devices, despite the claim otherwise, make drivers prone to error including failures in visual perception and in the inability to detect and react to hazards. A DAS vehicle will need more precise speed and a safe stopping distance. The good news is that technologies are being designed and laws are being passed to require new vehicles to install equipment to alert drowsy and distracted drivers (Schalit 2019).

SUMMARY

The paper has two major components devoted to:

- Explaining Delay: A stochastic car-following or driver behavior model, a collection of different stochastic differential equations, was derived and used to explain delay at a bottleneck operating at capacity.
- Preventing Delay: A Driver Assistance System (DAS) or Kalman Filter (KF) feedback control system was derived and used to prevent delay at a bottleneck operating at capacity.

Both model types describe a traffic merge by phases: *start-up*, *cruise* and *merge*. Phase models are derived and then linked together to form model structures that predict speed and location as vehicles proceed through the bottleneck. Both model types consider the effects of individual driver behavior, group driver behavior, traffic density, roadway geometry and traffic noise (speed volatility).

The stochastic car-following or driver behavior model features a Brownian motion models that mimic driver behavior under various conditions. The model also features constraints to assure drivers conform to a safe driving rule, i.e. maintains safe gaps between vehicles. Sensitivity analyses help explain the effects roadway geometry, operating at high traffic density and driver behavior have on queue formation and performance.

The KF feedback control system is designed to assists drivers. It manages vehicle speed and arranges vehicles in a "zipper" mode formation to efficiently travel through the bottleneck. The critically important feedback reference signal or tracking function, the mechanism for arranging vehicles while merging, is derived with a non-linear acceleration model.

The challenges associated with the driving public adopting autonomous cars and DAS technology in the future was discussed.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code generated or used during the study are available in a repository online in accordance with data retention policies (Ossenbruggen 2019a).

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List of Tables

Traffic Conditions at Roadway Capacity Targets for Optimum Performance		
$c = u^*/s_{safe}$ (v/h)	u^* (m/s)	s_{safe} (m)
2380	23.7	36.2

Risk Aversion and Safety Measures
$s_{ROR} = 26.9$ $s_{HCM} = 36.2$

TABLE 1. Targets for Optimum Performance

Sensitivity Analysis				
Traffic Noise		Flow	Speed	Headway
σ/u^*	σ	$\bar{q}(t_3) = \bar{u}(t_3)/\bar{s}(t_3)$	$\bar{u}(t_3)$	$\bar{s}(t_3)$
	(m/s)	(v/h)	(m/s)	(m)
0.00	0	2110	18.9	34.4
0.01	0.24	2090	18.8	34.4
0.02	0.48	2030	18.8	34.4
0.03	0.72	1700	17.9	37.8
0.04	0.96	1380	15.6	40.7
0.05	1.20	1120	13.6	46.2

TABLE 2. SCF Model Predictions

Predictions		
Speed Response	Speed $\bar{u}(t_3) \pm sd$ (m/s)	Headway $s = s_{safe}/2$ (m)
True	24.0 ± 0.14	18.1
Filtered	24.0 ± 0.05	18.1
Measured	24.3 ± 0.74	18.1

TABLE 3. KF Model Predictions

List of Figures

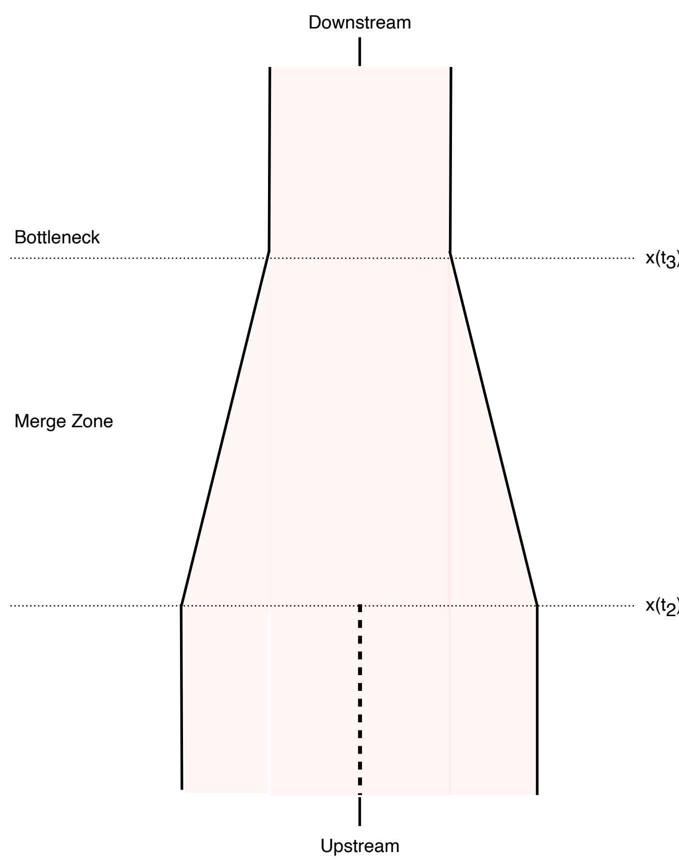


Fig. 1. Bottleneck schematic diagram.

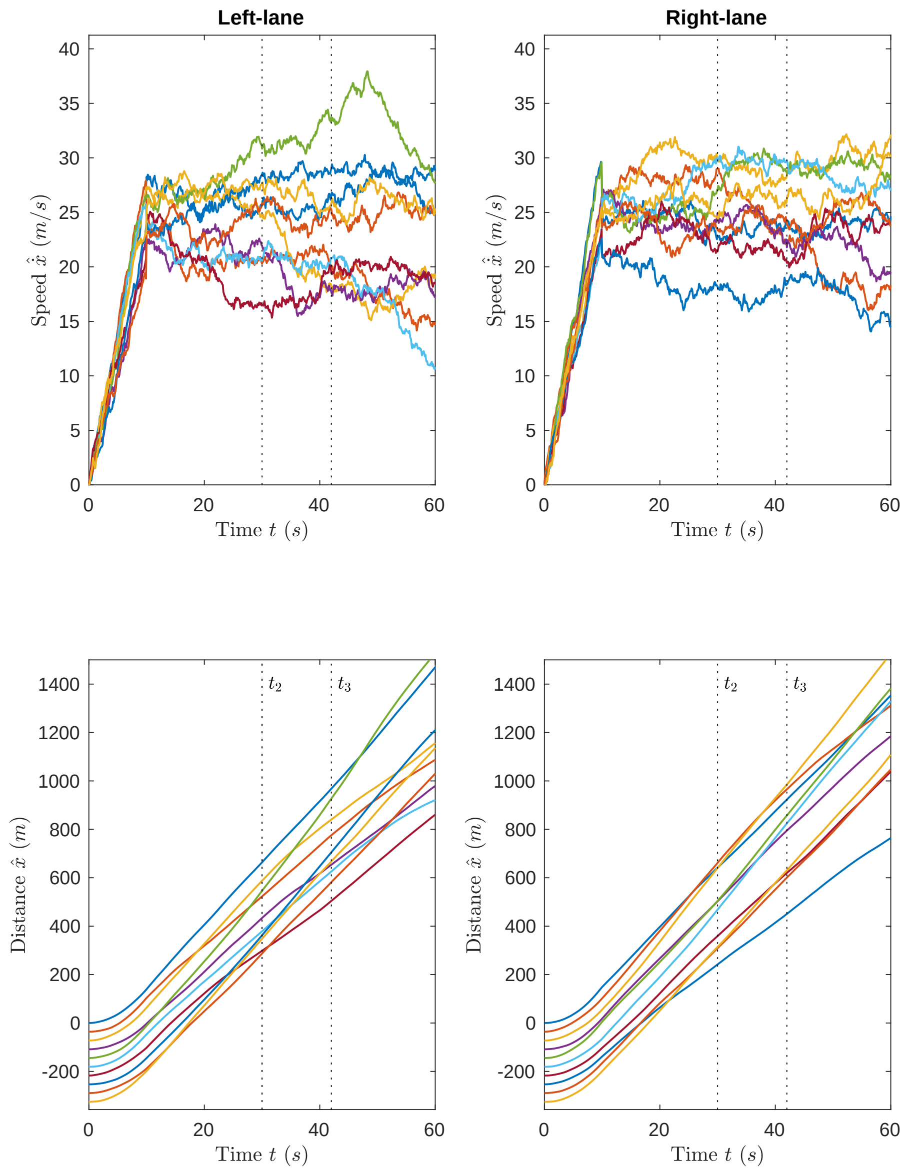
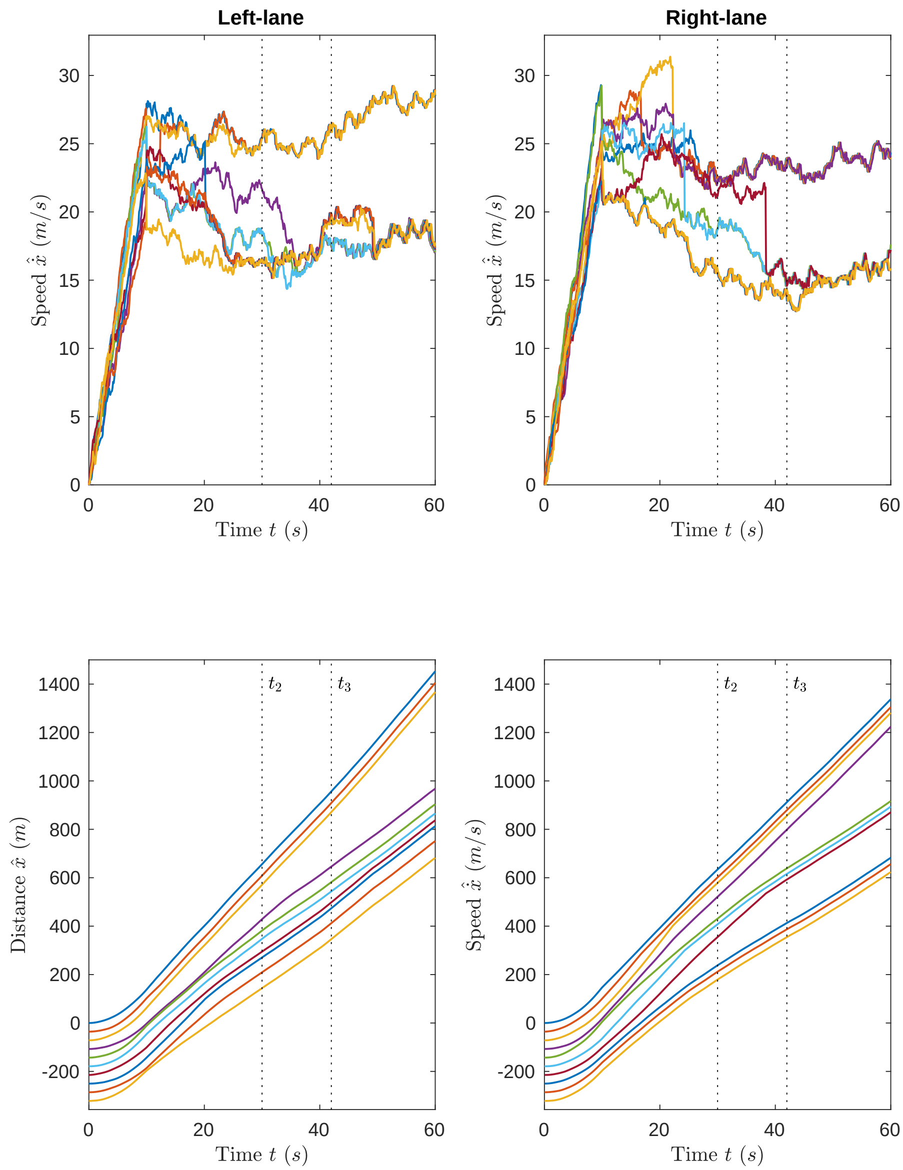


Fig. 2. "Unassisted" driver behavior by start-line for $0 \le t < t_2$ and $\sigma/u^* = 0.03$.



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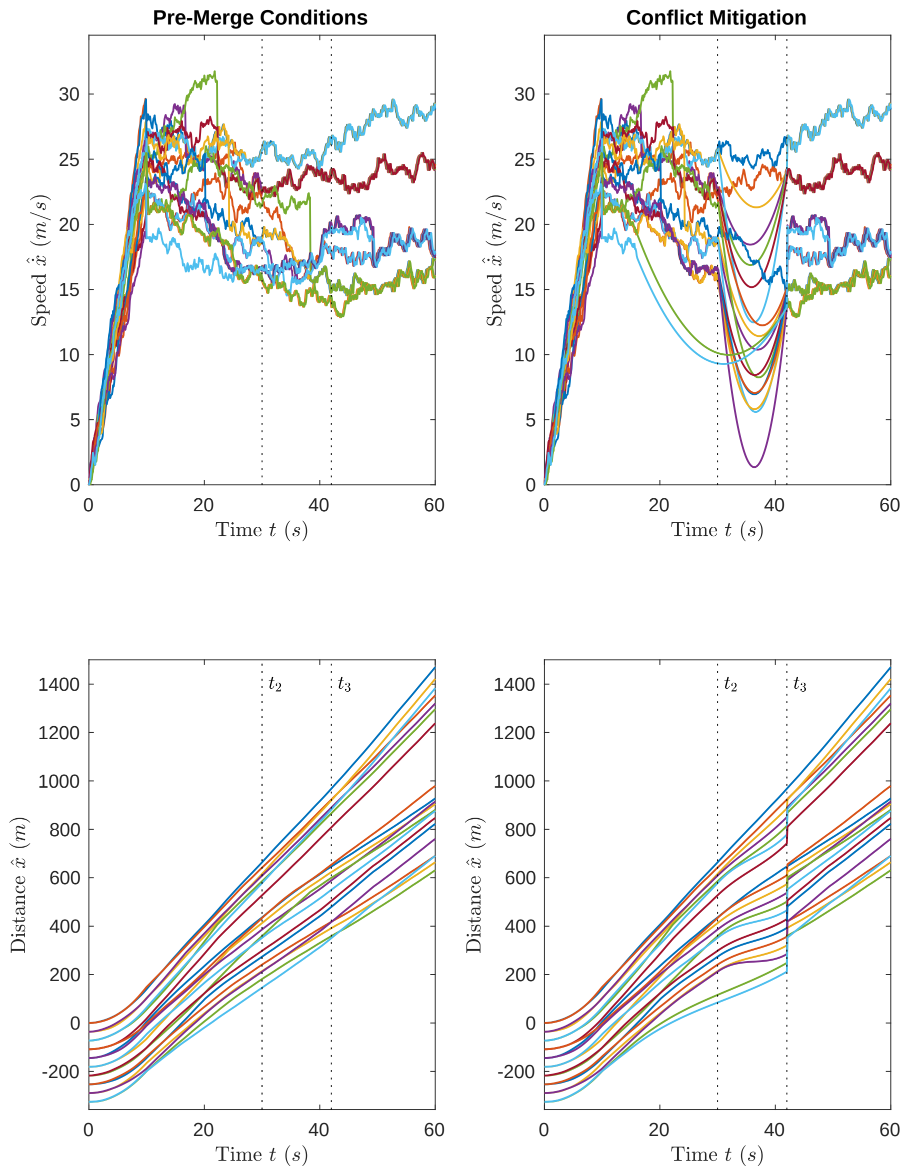

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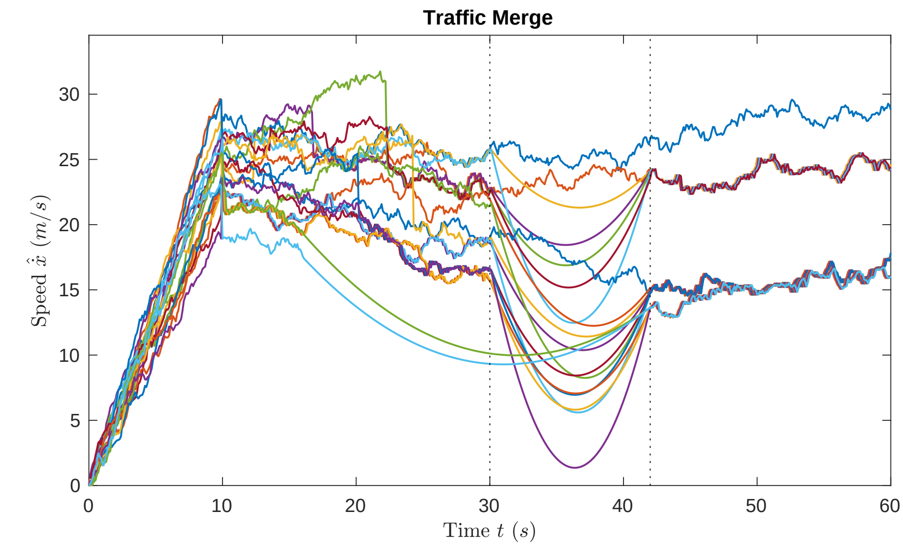


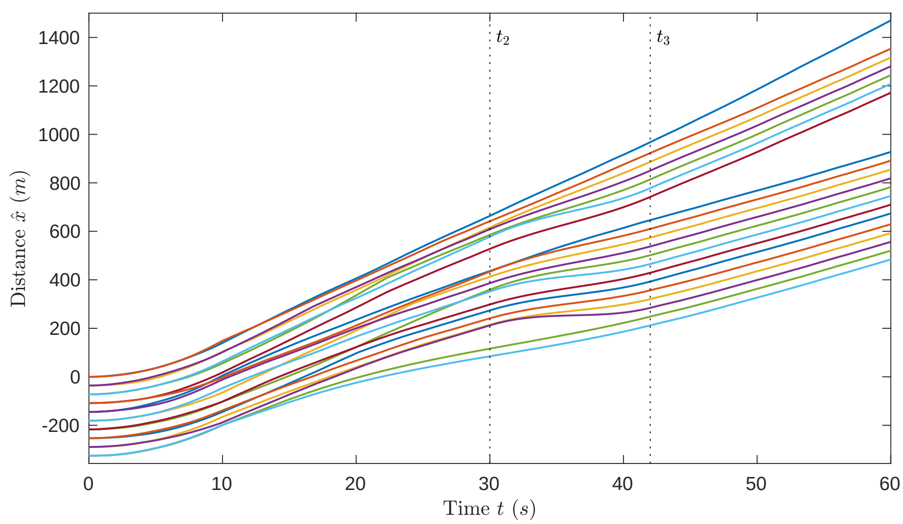


Fig. 5. Stochastic car-following model predictions for $\sigma/u^* = 0.03$.

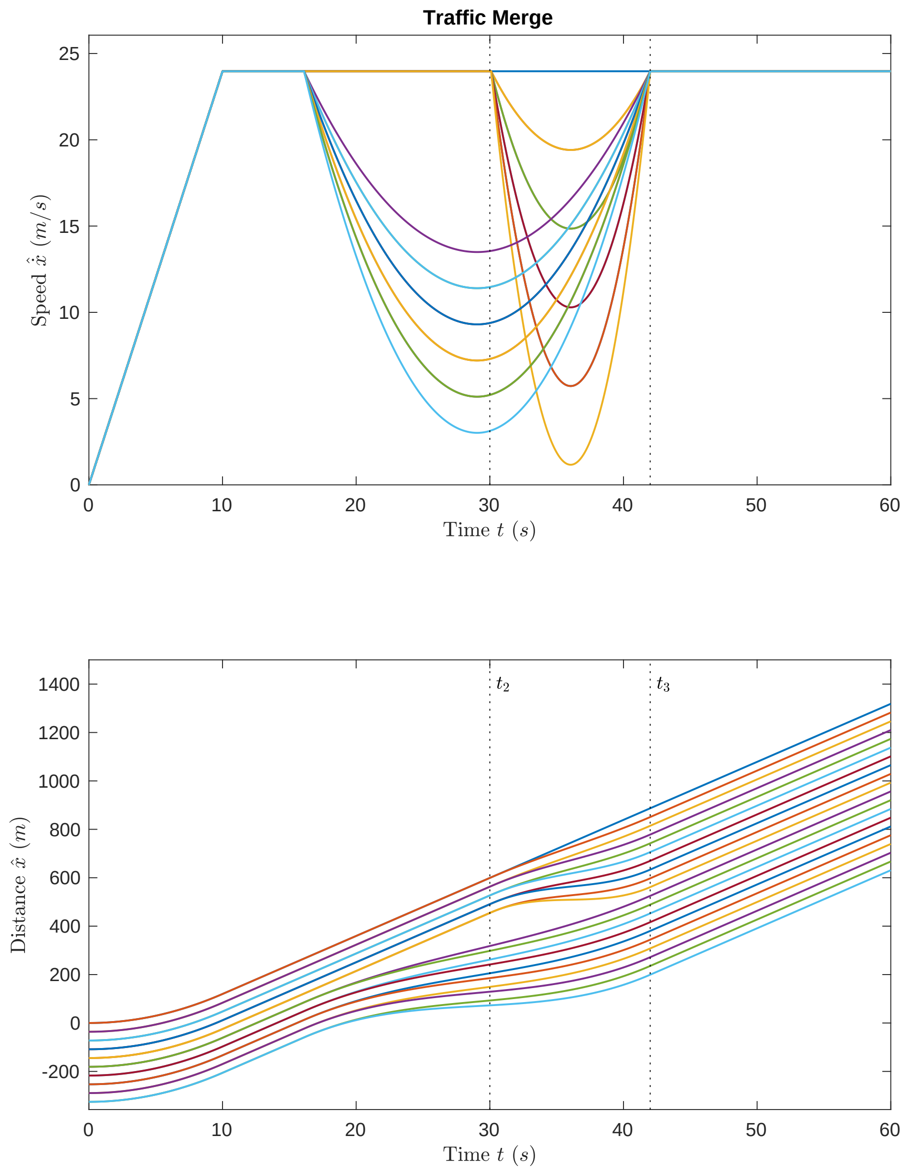


Fig. 6. Deterministic car-following model predictions for $\sigma/u^* = 0.00$.

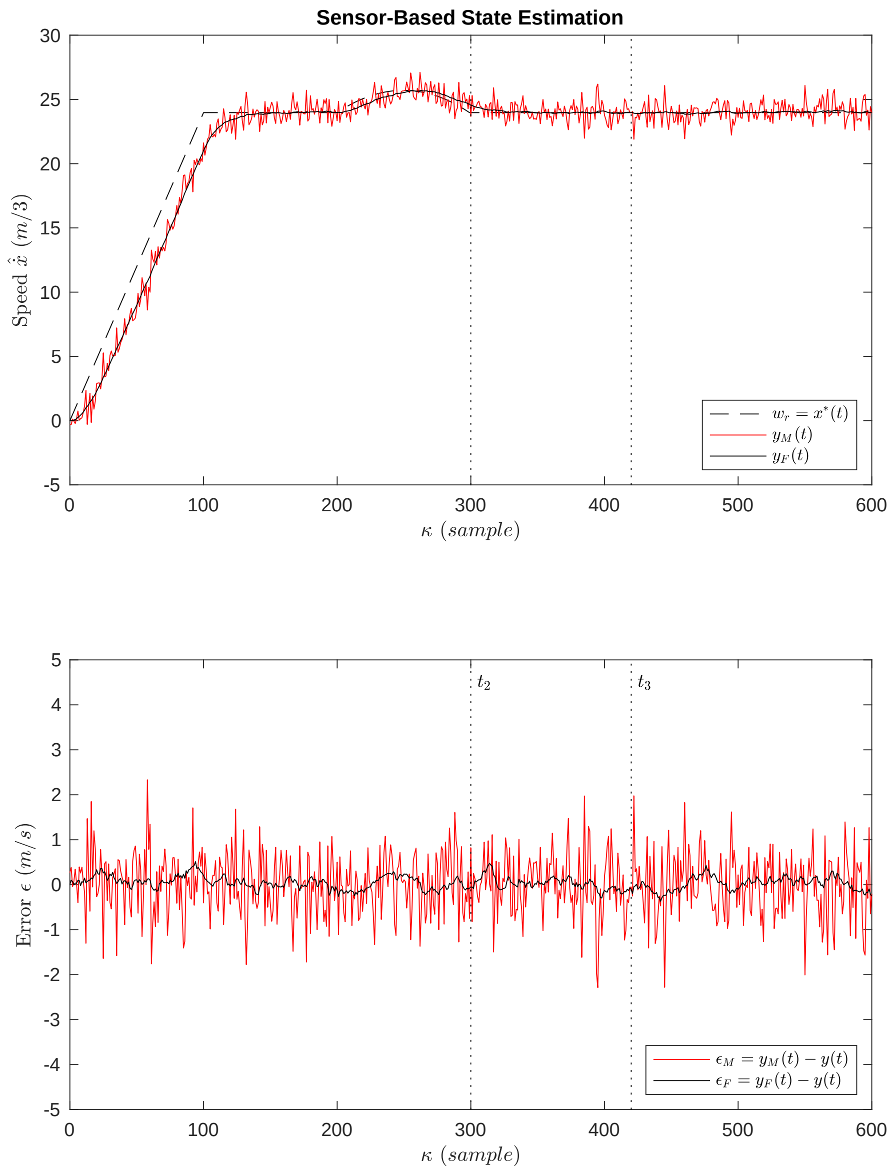
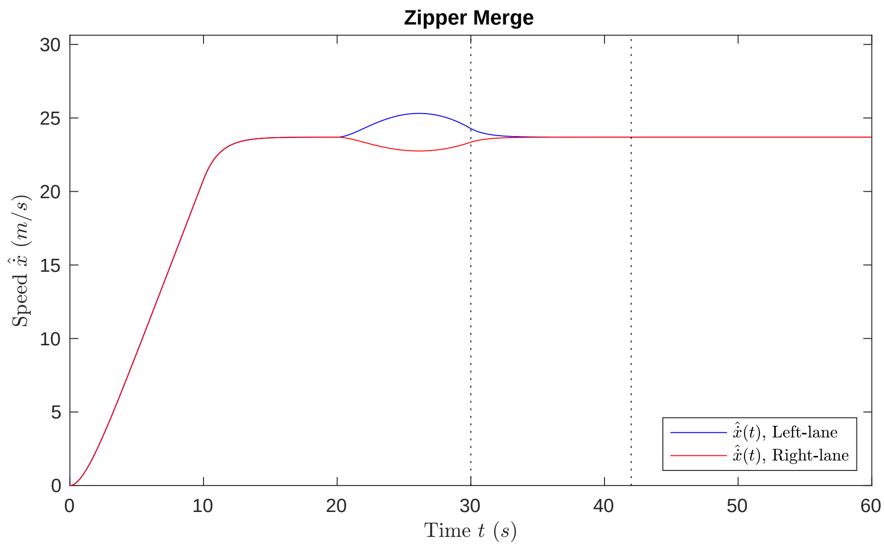


Fig. 7. State estimation for left-lane traffic using w_r: $w_d = 0.72$ (m/s); $w_n = 0.72$ (m/s).



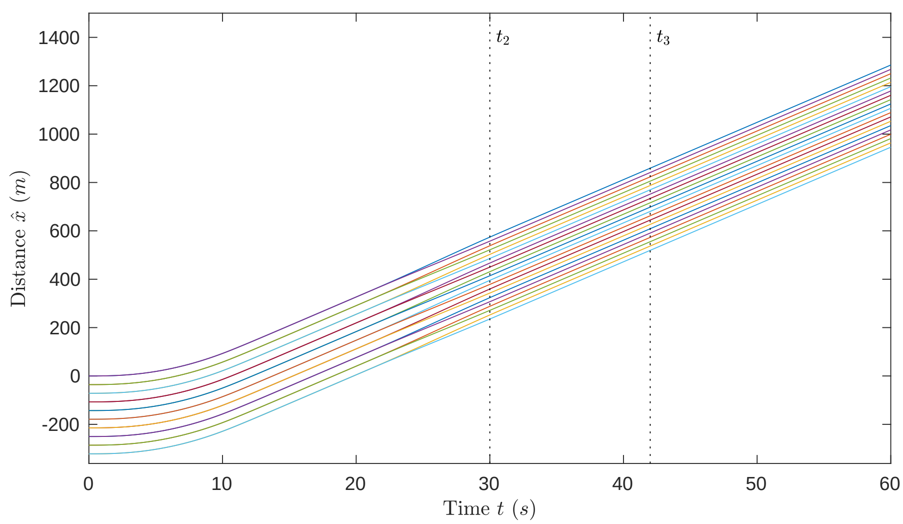


Fig. 8. A “zipper” merge with feedback control.

ABSTRACT

This study tests the feasibility of using a Kalman filter feedback control system at a bottleneck where drivers are forced to merge. Since the bottleneck is assumed to be operating at capacity, traffic delay is expected owing to high traffic density. The roadway geometry, a lane drop where two traffic lanes merge into one, plays a critical role. Individual and group driver behavior is known to cause traffic delay and to be the sole contributor to traffic noise. A driver behavior or stochastic car-following model is developed to study the effects of roadway geometry, traffic density and traffic noise on performance. The model features Brownian motion speed models that mimic driver behavior and simulates real-world bottleneck conditions where drivers start from a standing position, comfortably accelerate to a cruising speed, and then jockey for position when entering the bottleneck. All drivers are assumed to keep a safe headway. Since the model allows individual drivers to adjust their speed according to changing conditions, the model predictions help explain queue formation and performance. The feedback control system, which is assumed to use V2X (vehicle-to-everything) technology, uses an entirely different strategy. It assists drivers: (1) by managing vehicle speed and (2), by arranging vehicles in a "zipper" mode formation. A reference signal or tracking function, which proves to be vitally important in arranging vehicles for a "zipper" mode, is derived with a non-linear acceleration model. The impacts of deploying this scheme with V2X technology in a "Smart City" are discussed.

Keywords: Traffic breakdown, car following, congestion mitigation, Kalman Filter, stochastic processes, stochastic differential equations

Table1

Click here to access/download;Table;Table1.png

Traffic Conditions at Roadway Capacity Targets for Optimum Performance		
$c = u^* / s_{safe}$ (v/h)	u^* (m/s)	s_{safe} (m)
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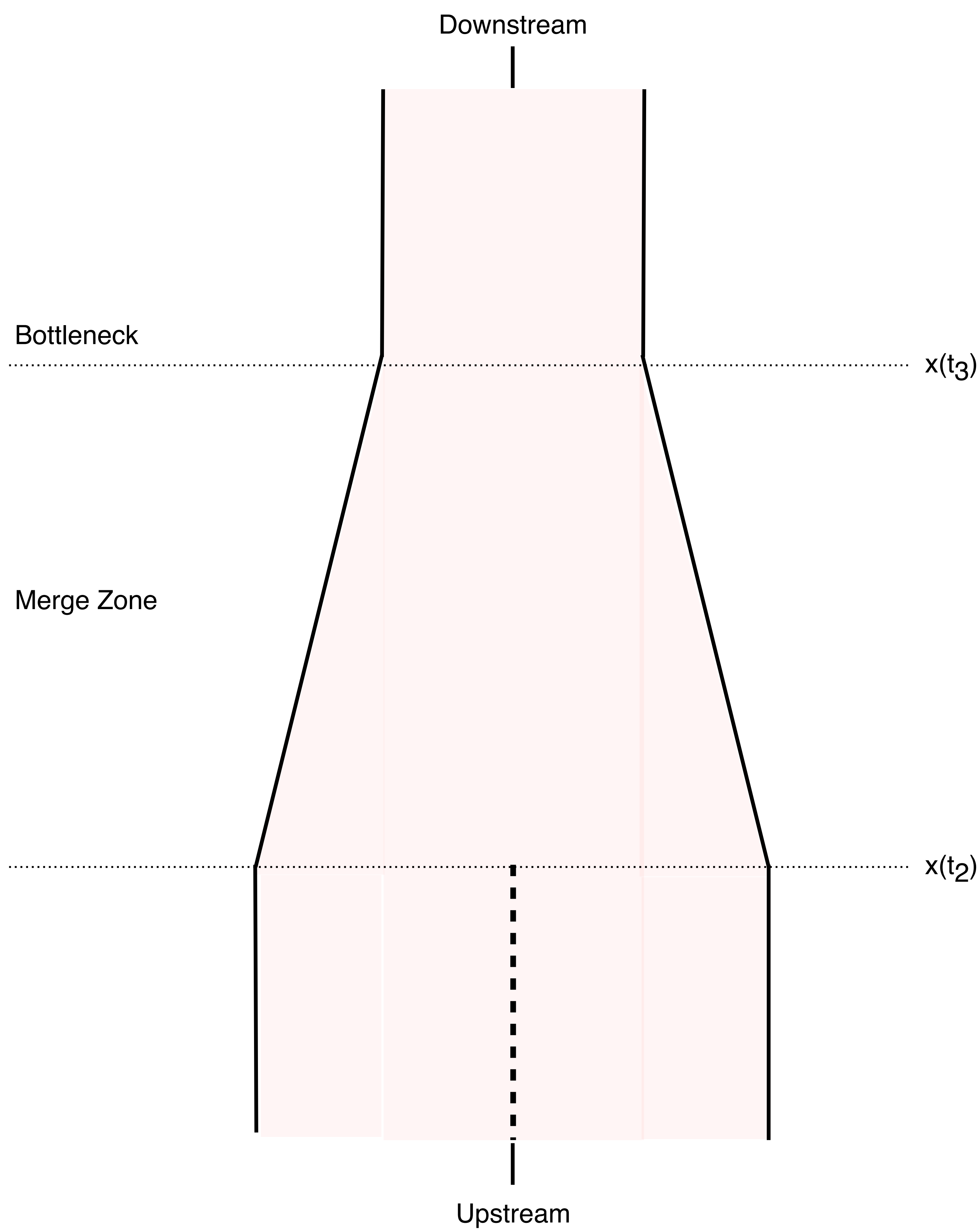
Risk Aversion and Safety Measures
$s_{ROR} = 26.9$ $s_{HCM} = 36.2$

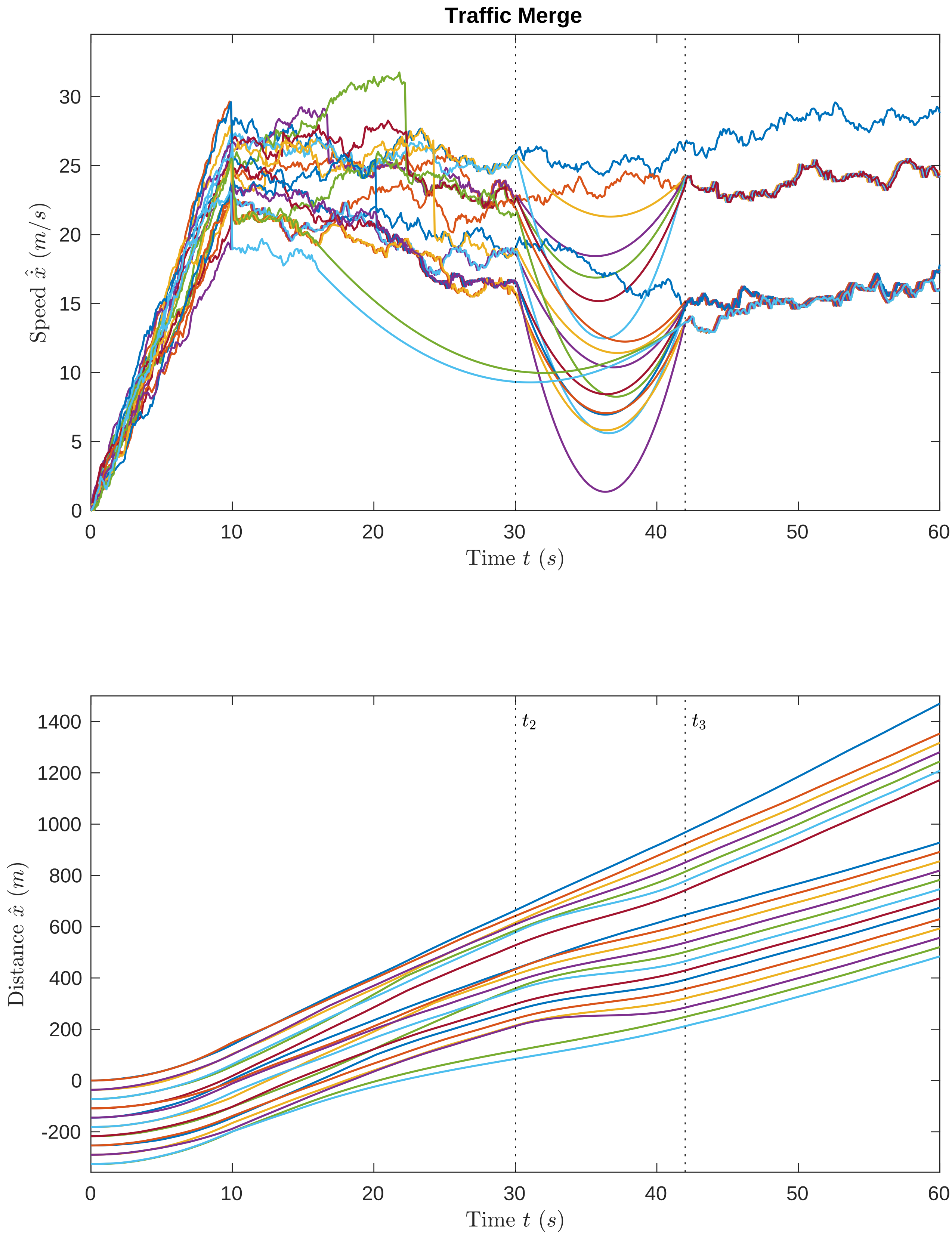
Table2

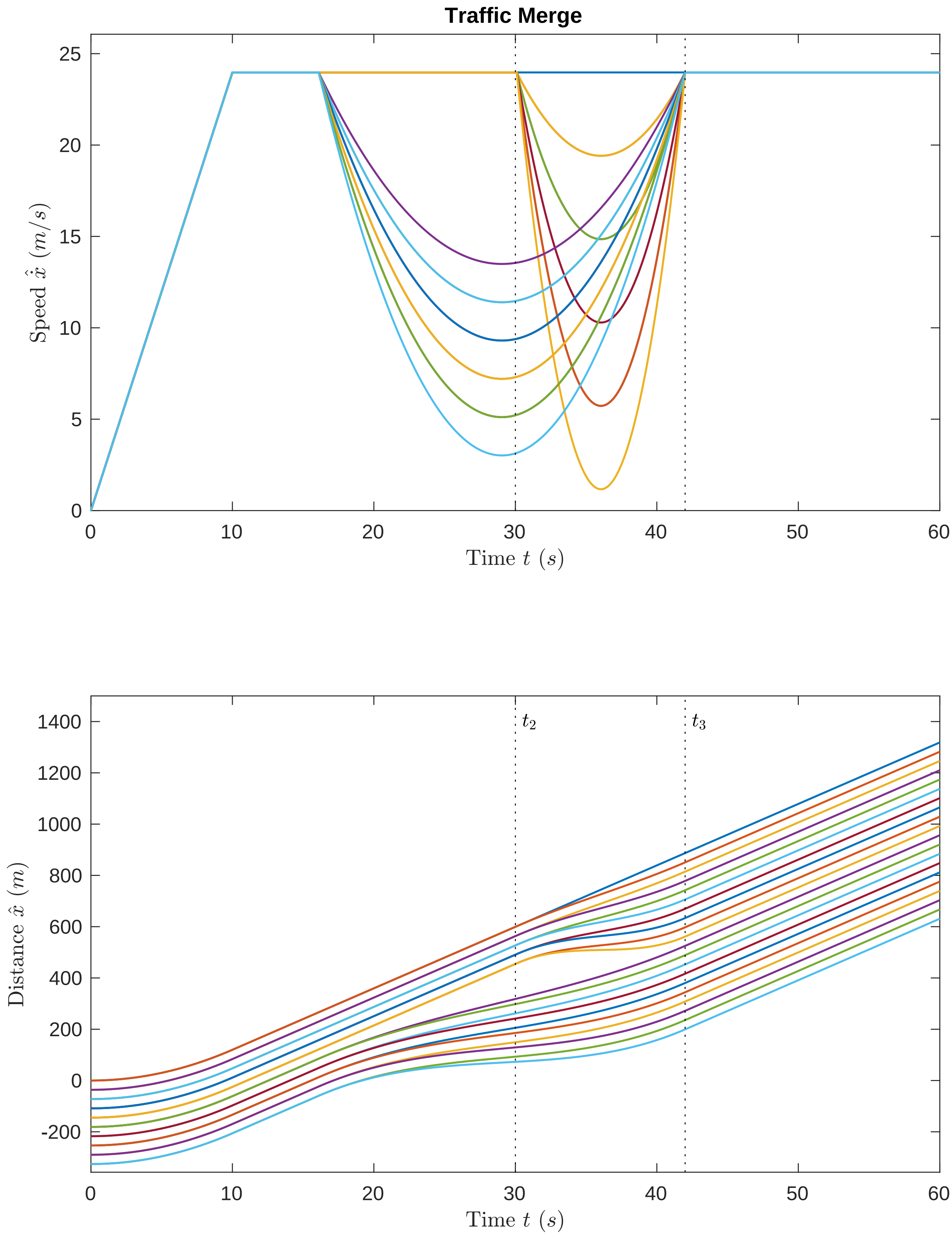
Click here to access/download;Table;Table2.png

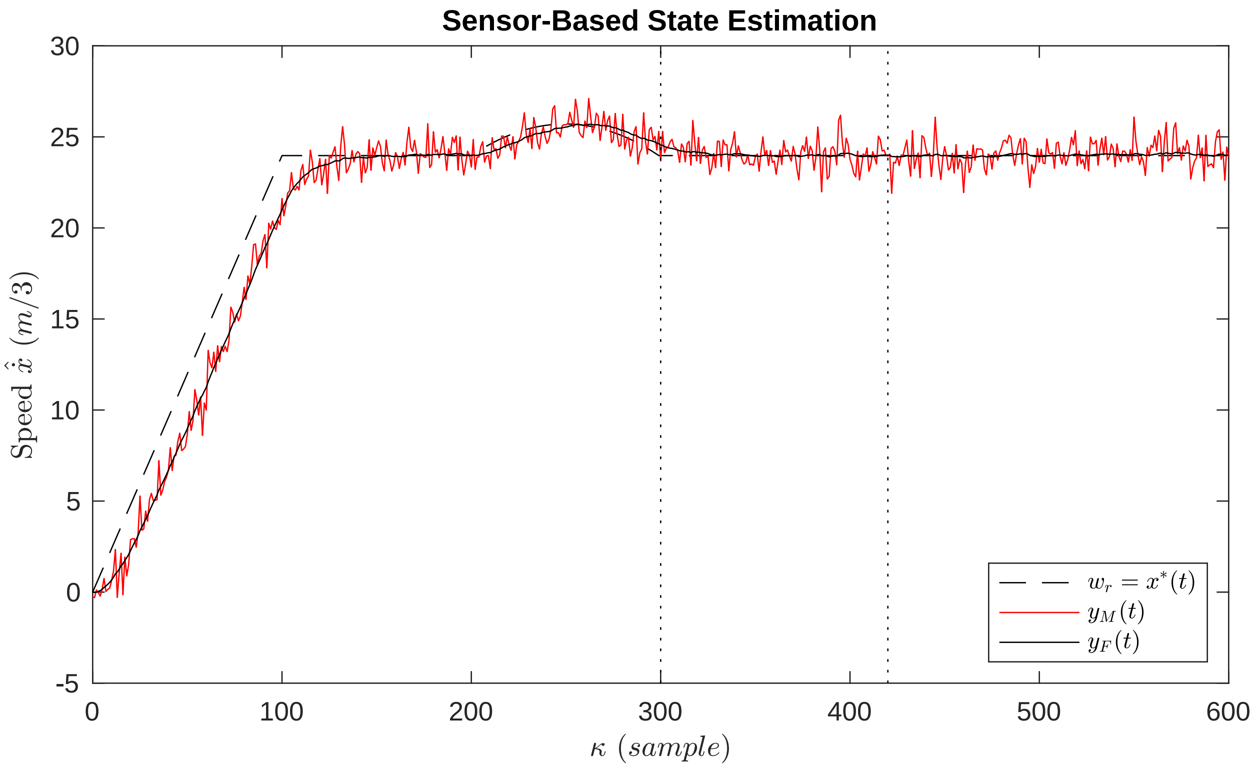
Sensitivity Analysis				
Traffic Noise		Flow	Speed	Headway
σ/u^*	σ (m/s)	$\bar{q}(t_3)=\bar{u}(t_3)/\bar{s}(t_3)$ (v/h)	$\bar{u}(t_3)$ (m/s)	$\bar{s}(t_3)$ (m)
0.00	0	2110	18.9	34.4
0.01	0.24	2090	18.8	34.4
0.02	0.48	2030	18.8	34.4
0.03	0.72	1700	17.9	37.8
0.04	0.96	1380	15.6	40.7
0.05	1.20	1120	13.6	46.2

Predictions		
Speed Response	Speed $\bar{u}(t_3) \pm sd$ (m/s)	Headway $s = s_{safe}/2$ (m)
True	24.0 ± 0.14	18.1
Filtered	24.0 ± 0.05	18.1
Measured	24.3 ± 0.74	18.1


Downstream
Bottleneck
x(t3)
Merge Zone
x(t2)
Upstream


Traffic Merge
Speed $\hat{x}$ (m/s)
Time t (s)
Distance $\hat{x}$ (m)
t_2
t_3
Time t (s)


Traffic Merge
Speed $\hat{x}$ (m/s)
Time t (s)
Distance $\hat{x}$ (m)
t_2
t_3
Time t (s)


Sensor-Based State Estimation
Speed $\hat{x}$ $(m/3)$
κ $(sample)$
$w_r = x^*(t)$
$y_M(t)$
$y_F(t)$
30
25
20
15
10
5
0
-5
0
100
200
300
400
500
600

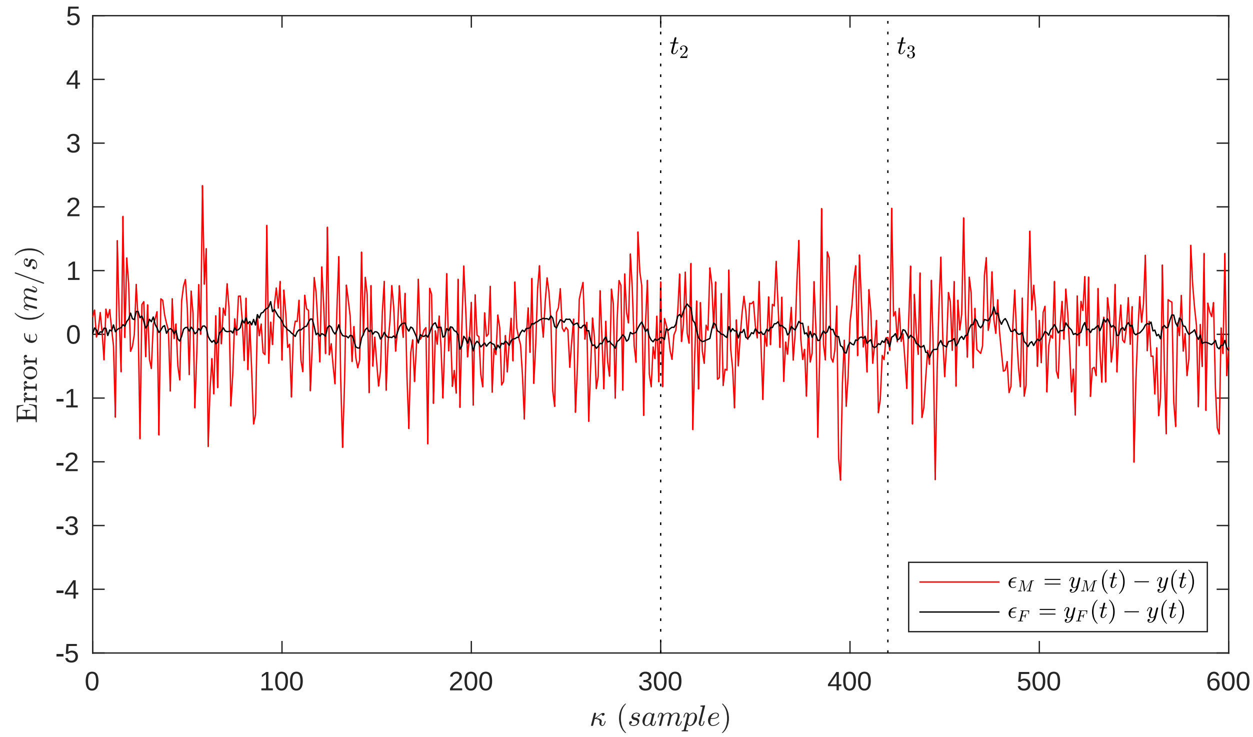
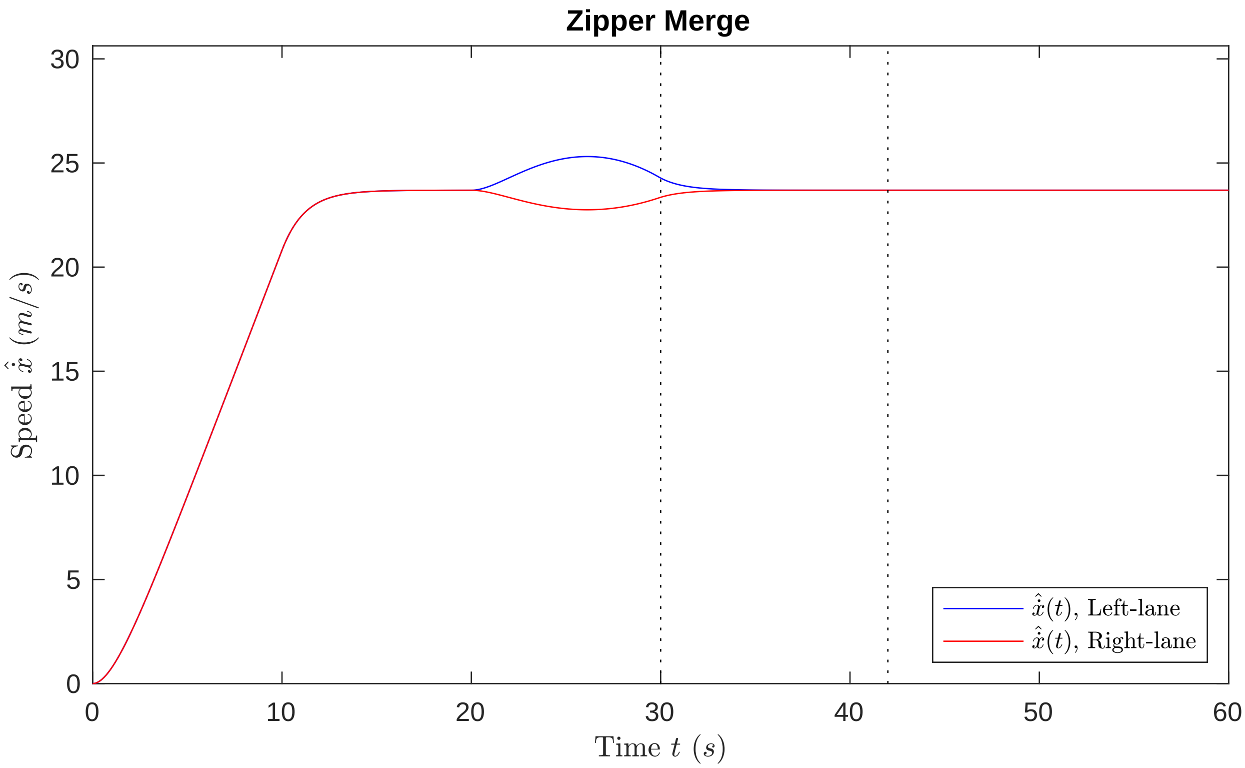

Error ϵ (m/s)
κ $(sample)$
t_2
t_3
$\epsilon_M = y_M(t) - y(t)$
$\epsilon_F = y_F(t) - y(t)$
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
100
200
300
400
500
600

Figure8

Click here to access/download;Figure;Figure7.pdf



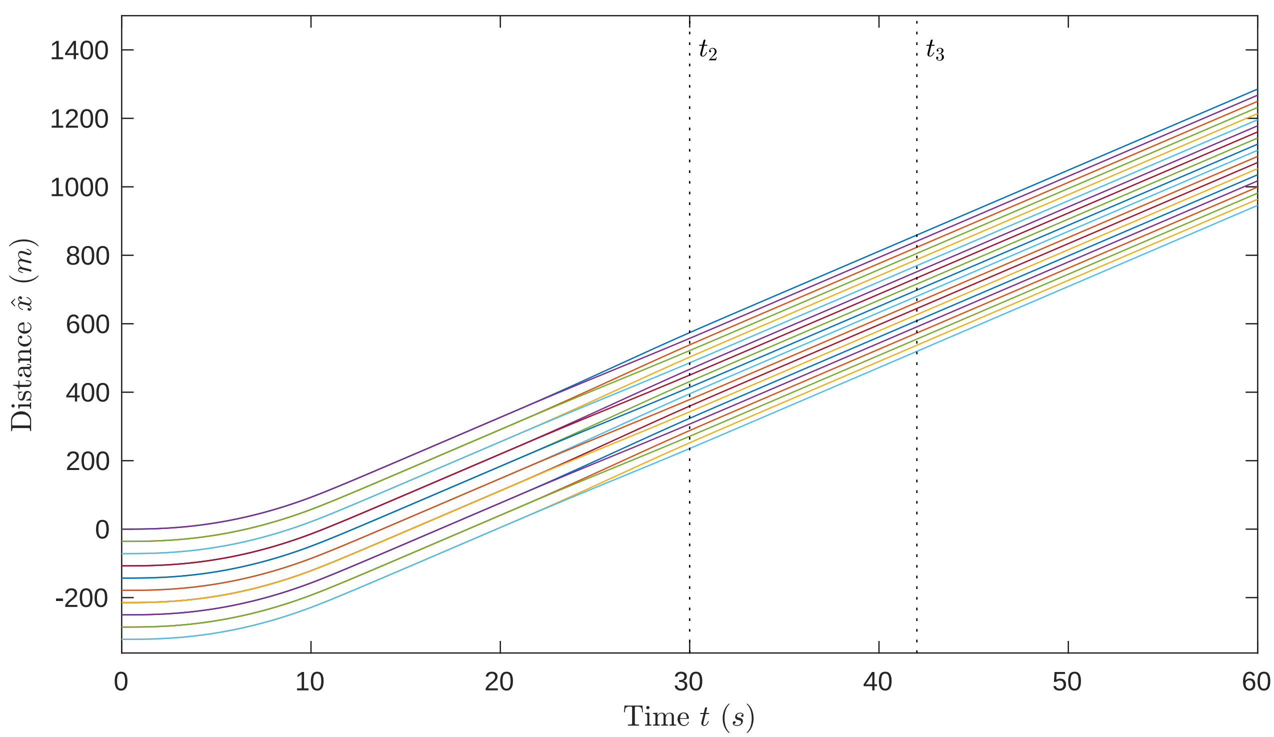
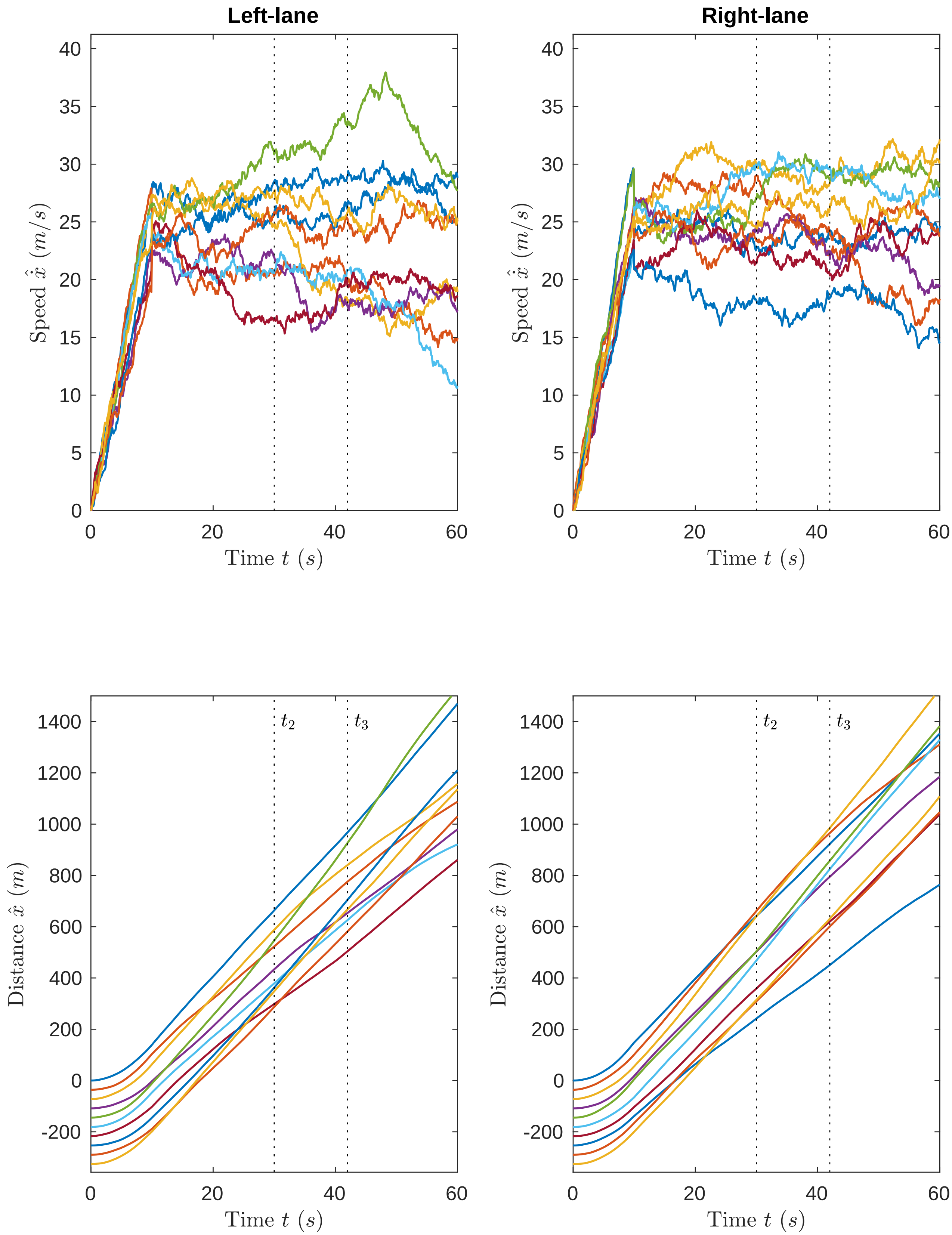


Figure2



Left-lane
Right-lane
Speed $\hat{\dot{x}}$ (m/s)
Time t (s)
Distance $\hat{x}$ (m)
t_2
t_3
0
5
10
15
20
25
30
35
40
0
20
40
60
-200
200
400
600
800
1000
1200
1400

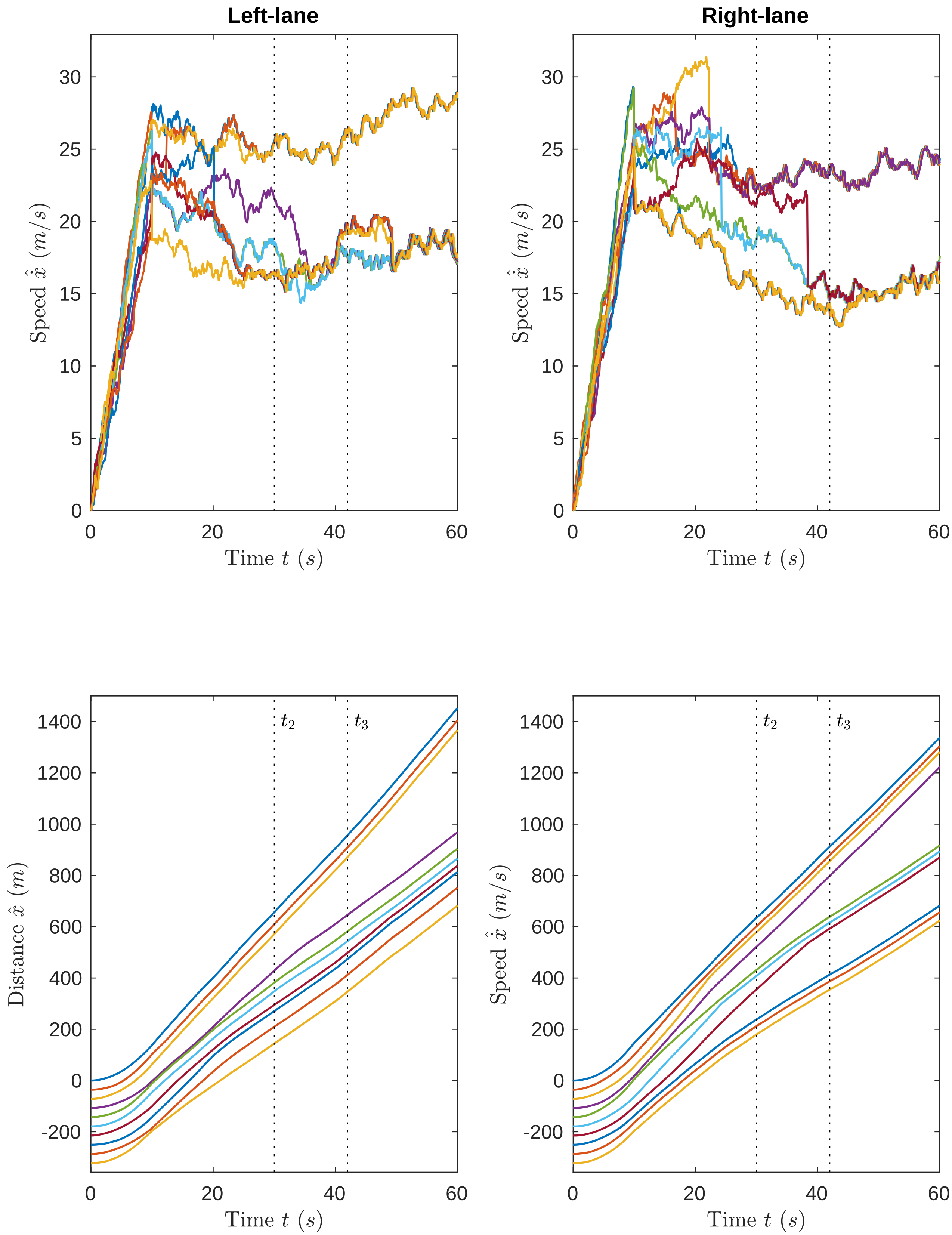
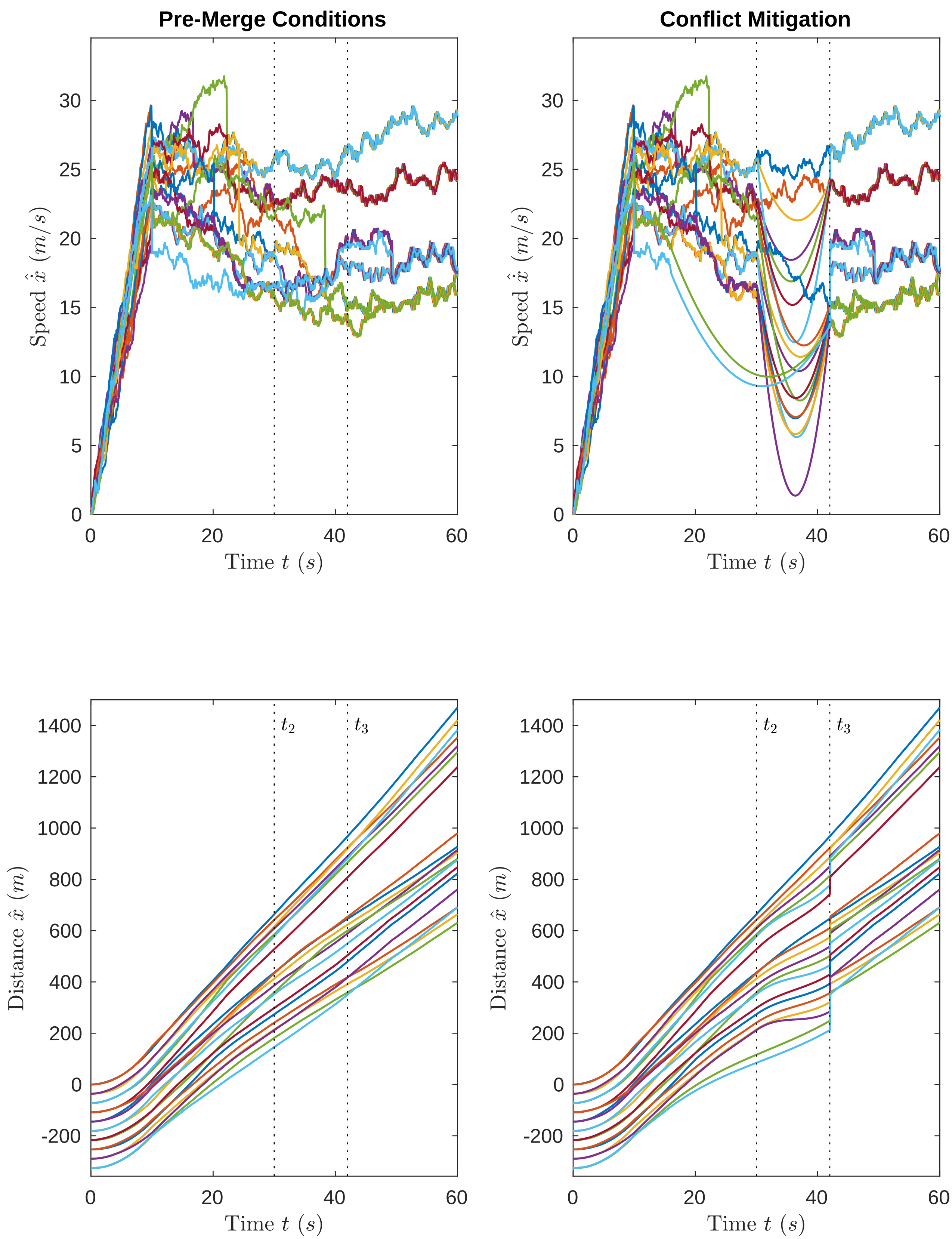

Left-lane
Right-lane
Speed $\hat{\dot{x}}$ (m/s)
Time t (s)
Distance $\hat{x}$ (m)
t_2
t_3

Figure4



Pre-Merge Conditions
Conflict Mitigation
Speed $\hat{x}$ (m/s)
Time t (s)
Distance $\hat{x}$ (m)
t_2
t_3

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Reviewers' comments:

Reviewer #1: This paper introduces a set of SDE models to explain breakdown of a bottleneck operating at capacity and derived a a DAS to prevent breakdown at such bottlenecks.

The topic is meaningful while the contribution on the methodology and performance analysis is vague.

The reviewer has below comments:

I agree with the reviewer's critique. The last comment asking why the paper is limited to 4 vehicles. It is an excellent. question.

Limiting the analysis to 4 vehicles resulted into a weak paper. I expanded to analysis and discussion to 20 vehicles traveling for 60 seconds. These changes required that my computer code to be improved and my paper to reorganized and parts rewritten. Figures in the original paper were replaced.

1. It should be clearly stated in the abstract and title that this paper is focused on bottleneck caused by lane drop, not a more general concept of breakdown.

The abstract has been rewritten. In lieu of focusing on breakdown, the paper focuses on delay, driver behavior and safety.

2. Before "merge option and safety" section, t_1, t_2 and t_3 are assigned values. Why are these time points regulated here? How is the duration for each phase estimated or calculated?

See the **Basic Concepts** Section. I define four zones: start-up, cruise free-flow, merge and cruise congested traffic zones. The merge zone extends from 30 to 42 seconds, which corresponds to a vehicle entering the merge zone and entering the downstream zone where owing to high density, the traffic is in a congested state.

3. Similar to the previous comment, how is the target speed calculated? Since the target speed significantly impacts the occurrence of the breakdown and capacity of the merging point, its value should be determined before completely introducing the formulation.

I added two subsections in the **METHODS** sections: *RiskAversion and Safety* and *Capacity of a Single Freeway Lane.* The target consists of a speed and a safe headway.

4. Since the analysis is conducted with a set of predetermined values for all the

parameters, the obtained results cannot serve as a general conclusion. To show sensitivity of some factors and effectiveness of breakdown identification model and the DAS, qualitative analysis and some expected results should be first introduced, followed by a comprehensive case study with different sets of values for the parameters. Using a single set of values for merging time, speed, and other factors cannot enable the model to simulate "realistic" conditions.

I added a section entitled *Sensitivity Analysis* in the **Explaining Traffic Delay** section. The traffic noise parameter is varied from zero to a value where the model simulation produces nonsensical output. The stochastic model becomes a deterministic model when the traffic noise parameter is assigned zero. It offers an interesting comparison deterministic world and my simulation of the real world. Figures 5 and 6.

5. At the end of "merge option and safety" section, the safe driving distance is derived based on capacity. However, such distance should not be utilized in the bottleneck analysis since vehicles under congestion or near a bottleneck may keep a shorter distance. This value is critical to following analysis and it should be derived with more careful formulation, if not from data collected on real-world segments.

I considered this suggestion. The computer, which now considers queue formation, was not addressed with 4 vehicles. The set of rules that a driver follows is more clearly presented in the revised paper. Equations 2 through 5 describes driver behavior for each zone. The material that follows explains how a driver changes speed to avoid crashing.

6. Does the assumption at the top of page 11 imply that all vehicles do not change speed between t_start and t_end?

No. The vehicles change speed. See # 5.

7. Why are 4 vehicles discussed in the DAS section? Does the proposed DAS has a limit for vehicles under consideration?