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A Case for Feedback Control to Prevent Delay

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Abstract:	This study was motivated by the work of researchers who conducted field experiments on roadways with no bottlenecks. ``Ring roads'' or single-lane circular roadways where passing was restricted. All drivers, who took part in these field studies, promised to maintain the same constant speed. They were unable to do so. The field tests showed the importance in the variability in speed, ``traffic noise.'' Like the field test, traffic noise plays a prominent role in this simulation study. In part one, the focus is on triggering traffic breakdown and queue formation. A stochastic car-following models are developed. They feature Brownian motion models that help explain the connection between driver behavior and traffic noise. In part two, the focus is on preventing traffic breakdown and queuing. State space modeling and feedback control using Kalman filtering are featured. Real-time noisy data are collected and recursively passed through a system that tracks a target, a target that is a function of time. All simulations in parts one and two of this study imitate the instructions given to the drivers in the ring road field experiments. The drivers start from rest, accelerate to the same constant speed, and then attempt to hold that speed through the duration of the experiment. In part one, the drivers fail. In part two, they succeed. To demonstrate the effectiveness of the feedback control approach, a worse case scenario is investigated. A ring road is assumed to operate at capacity thus, queuing and breakdown are expected. Testing and implementing the feedback control system in a ``smart city'' environment and its fate are discussed.
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A CASE FOR FEEDBACK CONTROL TO PREVENT DELAY

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ABSTRACT

This study was motivated by the work of researchers who conducted field experiments on roadways with no bottlenecks. "Ring roads" or single-lane circular roadways where passing was restricted. All drivers, who took part in these field studies, promised to maintain the same constant speed. They were unable to do so. The field tests showed the importance in the variability in speed, "traffic noise." Like the field test, traffic noise plays a prominent role in this simulation study. In part one, the focus is on triggering traffic breakdown and queue formation. A stochastic car-following models are developed. They feature Brownian motion models that help explain the connection between driver behavior and traffic noise. In part two, the focus is on preventing traffic breakdown and queuing. State space modeling and feedback control using Kalman filtering are featured. Real-time noisy data are collected and recursively passed through a system that tracks a target, a target that is a function of time. All simulations in parts one and two of this study imitate the instructions given to the drivers in the ring road field experiments. The drivers start from rest, accelerate to the same constant speed, and then attempt to hold that speed through the duration of the experiment. In part one, the drivers fail. In part two, they succeed. To demonstrate the effectiveness of the feedback control approach, a worse case scenario is investigated. A ring road is assumed to operate at capacity thus, queuing and breakdown are expected. Testing and implementing the feedback control system in a "smart city" environment and its fate are discussed.

Keywords: Traffic breakdown, car following, congestion, control, Kalman filter, stochastic processes

INTRODUCTION

Sugiyama et al. (2008) team conducted a simple but eloquent field experiment around a single-lane roadway. We call it a “ring-road” experiment. The research team instructed drivers to accelerate to a constant speed and then maintain that speed, a target speed u^*. At the start of the experiment, the vehicles were evenly spaced at a known distance, measured as a target headway s^*. Once they reached u^*, the drivers were unable to maintain that speed or maintain a constant headway (Villatoro 2019). Soon after the initiation of the experiment, moving queues were observed. Seconds later, some vehicles came close to stopping and then started up again. The Sugiyama research team concluded that small perturbations in speed caused “the emergence of a jam with no bottleneck.” In this paper, we call these small perturbations in speed, *traffic noise* and denote it as σ.

Every attempt is made to capture reality in this study. Our modeling efforts focus on simulating individual and group driver behavior as observed in the “ring road” experiment. As such, a *stochastic car-following* simulation model is derived to help explain why moving queues are formed and the role that σ plays in the process.

By collecting real-time traffic data, *feedback control*, state space models and Kalman filter, can theoretically be used to prevent moving queues from forming in the first place. A primary objective of the paper is to show that this goal can be achieved. Basically, a two-step approach is used. In part 1, the *stochastic car-following* simulation model is derived. It shows: *the system fails without control.* In part 2, using the information derived from part 1 and feedback control, it shows that *moving queues can be prevented.*.

The paper is organized as follows. The **METHODS** section contains two major parts or subsections. In the **1. Explaining Breakdown** subsection, the major challenge is to select a set of dynamic models and link them together in a manner that matches vehicle behavior observed in the “ring-road” experiment. In the **2. Preventing Breakdown** subsection, the role of collecting real-time data and incorporating these data into feedback control system are investigated. The **DISCUSSION** section contains a discussion on testing and implementing the feedback control system in a "smart city" environment and its fate.

METHODS

The "ring-road" experiment conducted by Sugiyama et al. 2008 and the video produced by Villatoro 2019 clearly show moving queues are formed. The simple road geometry coupled with no passing made the importance of traffic noise σ easy to identify. They present strong evidence that traffic noise σ plays a critical and predominate role in queue formation. The teams of Stern et al. 2018 and Tadaki et al. 2013 conducted similar field "ring-road" experiments and report similar results.

Computer simulation and modeling has played an important role in transportation covering a wide range applications using a wide range range of modeling approaches. Here is a sample of work dealing with stochastic modeling associated with collision avoidance, traffic management, queuing or stop-and-go waves, and driver behavior, factors associated with the "ring road" experiments discussed in part 1. Garcia-Costa et al. 2013 and Yin and Qiu 2012 have used it for traffic control and collision avoidance; Tomer et al. 2002 for stop-and-go wave analysis; and Angkititrakul et al. 2012 and Orosz et al. 2006 for studying driver behavior.

Kalman filtering is a "powerful tool for combining information in the presence of uncertainty (Bzarg 2015)." It has been used for various transportation applications using a variety of data collection methods and technologies. In part 2 of the this study, tracking speed over time is an important part of the discussion, therefore tracking is placed on the top of the list. One of the unique features of Kalman filtering is its ability to handle real-time data. Implementing a feedback control system will be discussed in the **DISCUSSION** section. The list shows how it has been applied in surface transportation tracking, management and design applications.

- Tracking

Ponsa et al. 2005 for forecasting vehicle location from data collected from a mobile platform. Sheu and Ritchie 2001to estimate time-varying lane-changing fractions and queue lengths for real-time incident management on surface streets. Chen et al. 2014 for estimating flow patterns using a landmark feature that is close to the road surface. Cheng and Hsu 2011 for traffic surveillance during the day and night. Lu et al. 2014 for vehicle tracking with video blob techniques. Almagambetov et al. 2012 for tracking taillights. (Nemati and Astrand 2014) for tracking people with laser scanning. Arguello and Berges 2018 for classifying objects within an intersection based on radar measurements. Kellner et al. 2016 for accident analysis using Doppler radar.

- Management

  Unzueta et al. 2012 for traffic counting using standard cameras. Friedrichs et al. 2010 for accident analysis using odometric data (yaw rate and speed). Liu et al. 2009 for accident analysis relying on large-scale construction of video surveillance equipment. Akhawaji et al. 2018 for detecting illegal parking using various analysis methods.

- Design

  Koo et al. 2004 for estimating lateral tire characteristics under various road surface and emergency driving situations. Casares et al. 2012 for assisting drivers with brake light data. Nakatsuji and Kawamura 2003 for assisting drivers in winter driving conditions using probe vehicles fitted with vehicular-motion sensors and a GPS device. Tsai and Ai 2017 for analyzing traffic safety on curves. Hashemi et al. 2017 for forecasting speeds of vehicles on curves. Lindner et al. 2009 for detecting lane markings with lidar. Nedevschi et al. 2004 for 3D lane detection. Dang et al. 2002 for depth detection from images. Mathew and Asari 2013 for tracking small targets with aerial photography.

The *stochastic car-following* simulation model is aimed at producing the results observed in these studies for a single traffic lane. The challenge is to show that the mathematical models chosen for this study can explain the conditions that lead to the development of moving queues.

To achieve this end, a *stochastic car-following* simulation model is developed. (a) It features a stochastic differential equation (SDE) model. The SDE model is a function of σ. Thus, the model accounts for the variability in speed observed in the observational data. (b) Noise or σ also affects vehicle spacing. It is assumed that when the noise becomes large enough, a queue will form owing to the interaction between leading and following vehicles. (c) Traffic breakdown is synonomous with queue formation. The chance of traffic breakdown is high when the traffic demand approaches or exceeds roadway capacity (Tadaki et al. 2013), thus traffic density of a single-lane freeway at capacity is used. By design, the vehicle spacing is sufficiently tight to promote queuing and breakdown. A sensitivity analysis is performed to determine the effects of traffic noise σ on traffic breakdown and queuing. (4) The conditions that lead to breakdown are fed into a feedback control system to tests its ability in preventing queuing. The simulated "ring road" experiment uses a sample size of $n = 20$ twenty passenger cars.

1. Explaining Breakdown

Now that the basic assumptions and properties of the *stochastic car-following* simulation model have been presented, the model is described. We start by describing a deterministic speed model that replicates the instructions given to each driver in the "ring-road" experiment.

The "Ring Road" Experiment

Each driver was instructed to drive his/her vehicle at the same constant speed u^*. To reach this speed from a standing position, each driver is assumed to accelerate at the same constant rate a. Given a start time is $t = 0$, all twenty vehicles will obtain the same speed at time t_1 and then maintain that speed:

$$u^*(t) = \begin{cases} at & \text{for } 0 \le t < t_1, \\ u^* & \text{for } t_1 \le t \end{cases} \tag{1}$$

Since $n = 20$ vehicles, there are twenty drivers that are denoted as $j = 1, 2, \ldots, 20$. Assuming each driver follows instructions, then $u_j(t) = u^*(t)$.

Vehicle locations are not the same. At start time $t = 0$, all vehicles are equally spaced s^* around a circular roadway. Thus,

$$x_j^*(0) = (j-1)s^* \tag{2}$$

The start locations are: $x_1^*(0) = 0$ for vehicle 1, $x_2^*(0) = -s^*$ for vehicle 2, $x_3^*(0) = -2s^*$ for vehicle 3, and so forth. The locations at times t are:

$$x_j^*(t) = \begin{cases} at^2 - s_j^* & \text{for } 0 \le t < t_1, \\ u^*t + at_1^2 & \text{for } t_1 \le t. \end{cases} \tag{3}$$

where t_1 is the time the vehicle reaches speed u^*. If all drivers precisely follow instructions, all vehicles will be equally spaced at any arbitrary time t.

Stochastic Differential Equations

Since moving queues were observed, the drivers were unable to follow instructions as described by (1) and (3). A *stochastic car-following* simulation model was developed to introduce traffic noise σ into the process by incorporating stochastic differential equations. They are of the form: $dX = \mu dt + \sigma dW$. Here, X is a generic random variable. The model consists of a deterministic and a stochastic component, μdt and σdW, respectively. W denotes *Brownian motion*. In lieu of solving the stochastic integral or Itô integral, $X(t) = x_0 + \mu t + \sigma \int_0^t dW$, the model is treated as a discrete system and a solution is obtained using simulation (Iacus 2008) Maybeck (1979). The stochastic integral $\int_0^t dW$ is simulated as $W(\Delta t) \sim \sqrt{\Delta t} \cdot N(0,1)$ where $N(0,1)$ represents a standard Normal distribution and Δt replaces dt.

The deterministic speed equations introduced above had the same values, $u_j(t) = u^*(t)$, at time t. Now, they are treated as random variables and denoted as $U_j(t)$. Depending of the magnitude of σ, the values of $U_j(t)$ can be profoundly different over time t and by vehicle or driver number $j = 1, 2, \ldots, 20$. Of course, the location $X_j(t)$ forecasts are also different.

Brownian motion plays an important role. Its effect on the $U_j(t)$ and $X_j(t)$ forecasts are most effectively visualized with traces of speed and location, which are simply denoted as $t - \dot{x}$ and $t - x$, respectively. Lower case letters of $\dot{x}$ and x are used because it is understood the traces are forecasts. In addition, the subscript j is dropped because the vehicle numbers being investigated are typically known. For example in car following, vehicle j is the *lead* vehicle and vehicle $j + 1$ is the *following* vehicle.

Stochastic Car-Following Models

No crashes were observed in the field study because each driver drove safely. At this point of our discussion, there is nothing to prevent crashes. They are easily detected. If lead and following vehicle traces cross one another, then a crash is assumed to occur. We denote this situation as or $s(t) < 0$. The distance between a *lead* vehicle, j, and *following* vehicle, $j+1$, is defined as $s(t) = x_{lead}(t) - x_{follow}(t)$.

Moving queues were observed in the field because drivers were unable to follow instructions. When a following driver's vehicle became too close to the vehicle in front, we denote it as $s(t) < s^*$.

To simulate field conditions, both the $s(t) < s^*$ and $s(t) < 0$ conditions must be eliminated. It is called a "correction process." It is a function of times t_V, t_S and t_E. The subscripts V, S and E refer to the times when a driver detects a violation, starts to decelerate, and returns his/her vehicle back to normal, i.e., the speed and spacing are considered safe. The "correction process" consists of four steps.

First, it is assumed that all simulated drivers are alert and will avoid crashing by detecting a safe headway violation, either $s(t) < s^*$ or $s(t) < 0$. t_V is the first instance of time where the following inequalities where $s(t_V) < s^*$ or $s(t_V) < 0$ occur.

Second, it is assumed that the following driver will not respond instantaneously but will require 2.5 seconds to initiate deceleration, $t_S = t_V + 2.5$.

Third, the value of t_E is the time the following driver achieves speed u^* and is traveling at distance s^* behind the lead vehicle. The value of t_E needs to be forecast. At t_S, the driver has the following information available at his/her disposal: $u_{follow}, u_{lead}, x_{follow}$ and u_{lead}. This information is used to construct (1) a *sight-line* equation for the following vehicle driver, $x_{follow}(t) = x_{follow}(t_S) + u_{follow}\Delta t$, and (2) a *straight-line* equation for the lead vehicle, $x_{lead}(t) = x_{lead}(t_S) + u_{lead}\Delta t$. By setting the two equations equal to each other, Δt can be calculated and $t_E = t_S + \Delta t$ estimated.

If $\Delta t > 0$, the following vehicle speed and location trajectory can be calculated using a nonlinear acceleration relationship:

$$a(t) = \alpha - \beta t \text{ for } t_S \leq t < t_E \tag{4}$$

where the values of α and β are unknown. Speed $u(t)$ and location $x(t)$ equations (not shown) are obtained by integration. The values of α and β are estimated within the stochastic car-following model algorithm. Given two equations, $u(t)$ and $x(t)$, and the times t_S and t_E, the two unknowns can be calculated. At t_S, $u_{follow}(t_S)$ and $x_{follow}(t_S)$. At t_E, $u_{follow}(t_E) = u_{lead}(t_E)$ and $x_{follow}(t_E) = x_{lead}(t_E) - s^*$. These two relationships assure the following vehicle is traveling at the same speed of the lead vehicle at a safe distance headway s^*.

Four, double check the estimates made in steps 1 through 3 are legitimate and the $s(t) < s^*$ condition is not violated. Owing to the stochastic nature of the process, steps 1 through 3 can result in erroneous predictions. For example, Δt must be a positive value. If $\Delta t < 0$, then a simulated driver is looking in his/her rear mirror and adjusting vehicle that way. This erroneous prediction is corrected by finding each $s(t) > s^*$ violation and adjusting the following vehicle speed to be equal the lead vehicle speed and placing the following vehicle distance s^* behind the lead vehicle at each violation time. Another situation arose. Since there are no restrictions placed on following drivers, it is possible for these drivers to be traveling at speeds greater than their lead vehicles. This is fine as long as $s(t) < s^*$. The following vehicle is narrowing the gap and catching up to the lead vehicle. The following vehicle catches up when $s(t) = s^*$. At this point in time, the following vehicle will decelerate and will assume a speed equal to the lead vehicle and adjust its headway.

Traffic Performance

It is difficult to visualize the $s(t) < s^*$ violations described in the preceding paragraph, the nature of the correction and the role that chance plays. Compare $t - \dot{x}$ and $t - x$ traces shown in Figures 1 and 2. They are quite different. Regardless, they are derived from the same model using the same model parameter assignments of u^*, s^* and σ. There is one exception; their random seed assignments are different: SEED = 125 and 127, respectively.

The values of u^* and s^* are derived from the capacity assignment of c. Recall, to increase the chance of traffic breakdown, the "ring road" is assumed to operate at capacity c. According to Highway Capacity Manual (TRB 2010) guidelines, the capacity of a single freeway lane is 2380 $passenger - cars/hour/lane$. It operates at a speed of $u^* = 23.7\ m/s = 85\ km/h$ (53 mph) and a density of $k = 28\ pc/km/l$ (45 $pc/m/l$) and $s^* = 1/k = 35.8\ m$.

Choosing σ value is critical. It is discussed in more detail in the *Model Calibration* subsection. Traffic noise is assigned to be $\sigma = 0.355\ m/s$. This value is used throughout the paper except where noted.

Now, compare the information given in Figures 1 and 2. First, focus on Figure 1. The two left panels show the trajectories for the lead and following vehicles with no corrections. The right panels are for the same vehicles with corrections. At first glance, it may seem odd that a correction took place at all. The two vehicles on the left accelerate at approximately the same rate for the first 10 seconds and then the lead vehicle speeds up and the following vehicle slows down. As time progresses the distance between them widens. The trajectories to the right show the lead vehicle to progress in an identical manner as to the one on the left. However, the following vehicle violates the $s(t) < s^*$ condition at time t_S as shown by the open circle. At this point, the following vehicle speeds up but does not exceed the speed of the lead vehicle. When it catches up at around $t = 25$ seconds, it maintains the same speed of the lead vehicle and also keeps a safe distance behind the lead vehicle. It is interesting to note that vehicle spacing at $t = 60$ is less with corrections than the spacing of the left panel with no corrections. The only explanation is chance, the luck of the draw.

Contrast this information with Figure 2 where everything is the same as in preceding paragraph except the SEED = 127. It shows $t_S \approx 30$ seconds. The following vehicle has a speed greater the following vehicle until this time when the two vehicles have the same speed.

The $t-\dot{x}$ and $t-x$ trajectories, given in Figures 1 and 2, are part of a larger study, shown in Figures 3 and 4, for a sample of $n = 20$ passenger cars. The "uncorrected" trajectories show vehicles will crash, several $t - x$ trajectories cross, $s(t) < 0$. It is difficult to discern but there are a few $t-x$ trajectories that do not violate the unsafe $s(t) < s^*$ condition. The "corrected" trajectories in the right panels show the effects of removing the $s(t) < 0$ and $s(t) < s^*$ violations.

Again, chance plays a role. After time $t > 10$ seconds, vehicles tend to cluster where groups of vehicles tend to travel at the same speed. In Figure 3, there are two clusters of approximately eight vehicles in a group. This is most easily seen for $t > 40$ seconds. In Figure 4, there are four clusters of different sizes for this range. Vehicles in these clusters tend to slow down and then speed up again as observed in the "ring road" experiment.

Table 1 compares the average speed $\bar{u}(t)$ at $t = 10$, 30 and 60 seconds. The average speeds show a decline in both simulations at $t = 30$. At $t = 60$, the average speed decreases for one simulation and increases for the other. It is also interesting to note that for *Seed* = 127 that $\bar{u}(10) \approx \bar{u}(60)$, the average speed of the roadway at capacity. The average flows and densities show a great deal of volatility at these times when the traffic noise is $\sigma = 0.71$

m/s. When measured as a σ/u^* ratio, σ is a relatively small numerical percentage of u^*. It is 1.5%

Model Calibration

From a traffic engineering point of view, it is not clear that 1.5% is truly a "representative" assignment (Hoogendoorn and Hoogendoorn 2010). The decision to use it was arrived at by a process of elimination. The principle tool used in narrowing the choice was the $t - \dot{x}$ and $t - x$ trajectories. The statistics listed in Table 1 offer some interesting insight and helped form an opinion.

At $\sigma/u^* = 0\%$, the stochastic car-following model becomes a deterministic model where no moving queue can form. At $\sigma/u^* = 0.5\%$, the average number of $s(t) < s^*$ violations was surprisingly large, suggesting that the vehicles become tightly clustered and continued to move at high speeds of around 85.3 km/h, which is judged to be unlikely. At $\sigma/u^* = 1.0\%$, a similar pattern was observed but the clusters were less tight and less rigidly structured. Hence, it was decided that these trajectories resembled moving queues. Thus, the lower bound of the σ/u^* ratio range was established.

Larger values of σ/u^* ratios were investigated as shown. Given the stochastic nature of the process, it was difficult to decide. For example, the performance forecasts for the seeds of 125 and 127 at $\sigma/u^* = 1.5\%$ shown in the table and Figures 1 and 2 are different but defensible.

As σ/u^* was increased, the vehicle speeds became more chaotic. In one simulation run at $\sigma/u^* = 3\%$, a few speed forecasts were negative. The vehicles must move forward. Given this result, the upper range was established. Thus, $1\% \leq \sigma/u^* \leq 3.0\%$ was established.

2. Preventing Breakdown

The goal of a state space model is to infer information about future states of a system given observations of these states as time progresses (QuantStart Team 2019). Feedback control uses a recursive procedure. Data points are collected at a given time and then used to make a one step ahead forecast. During each step, the noise in the system is minimized.

In our case, a speed $u(t)$ value is observed at time t and then used to forecast the speed $u(t+\Delta t)$ for the next time step $t+\Delta t$.

A State Space Model

To obtain the desired forecasts, Newton's Second Law of Motion, $F = ma$, is used and then analyzed with a linear state space model:

$$\frac{d}{dt}\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{5}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \tag{6}$$

where $\mathbf{x}$ and $\mathbf{y}$ are the state space and observation matrices, respectively. For the "ring-road" experiment, $\mathbf{x} = dx/dt = \dot{x}$ for vehicle speed, and $\mathbf{u} = f$ for the actuation force. The model reduces to:

$$\ddot{x} = \left(\frac{-b}{m}\right)\left(\dot{x}\right) + \left(\frac{1}{m}\right)\left(f\right) \tag{7}$$

$$y = \left(1\right)\left(\dot{x}\right) \tag{8}$$

The drag force b term, estimated using a first-order Taylor-series expansion, is derived from the nonlinear equation, $f_d = \rho \cdot C_d \cdot A \cdot u^2/2$ where ρ is the air density, C_d is the vehicle drag coefficient, A is the frontal area of the vehicle, and u is vehicle speed. All drivers, who are assumed to be driving an average American passenger vehicle, will accelerate by applying force $\mathbf{u} = f$. The drag force is estimated to be equal to $f_d = b\dot{x} = 250\ N$ ($56.3\ lb$) when traveling at $\bar{u} = 85\ km/h$ ($53\ mph$) with $b = 21.1\ Ns/m$ ($lb - s/ft$).

Feedback Control

Now that the equation set of (7) and (8) has been established, feedback control can be initiated. Excellent sources of information are contained in the writings of Durbin and Koopman (2012), Doyle et al. (1992) and Anderson and Moore (1979). In our study, a linear quadratic regular (LQR) and linear quadratic estimator (LQE or Kalman filter) (Duriez et al. 2017) and a scaling factor (MATLAB@9.2 2019) are applied.

First, the LQR and scaling factor are applied. Their effects are shown in the top-left panel of Figure 5. Most importantly, the $u_r(t)$ traces the target $u^*(t)$ signal. The scaling factor eliminates the steady state error. Before applying the scaling factor, the untreated signal is shown as $u(t)$.

Next, the $u_r(t)$ signal is fed into (7) and (8) and process noise w_d and sensor noise w_n are added:

$$\ddot{x} = \left(\frac{-b}{m}\right)\left(\dot{x}\right) + \left(\frac{1}{m}\right)\left(f\right) + w_d \tag{9}$$

$$y = \left(1\right)\left(\dot{x}\right) + w_n \tag{10}$$

where w_d and w_n are assumed to be zero-mean Gaussian white noise. A estimator with a Kalman filter gain for vehicle speed is constructed with LQE. To demonstrate the effectiveness of feedback control, a worse case scenario is presented. The process and signal noises are assumed to be equal and equal to the same value specified above for the SDE and car-following models discussed above: $w_d = w_n = \sigma$ where $\sigma/u^* = 3\%$ or $\sigma = 0.71\ m/s$.

Consider the information presented in the top-right and bottom-right panels. The input speed $u_v(t)$ is noisy because it contains the effects of both the process w_d and sensor noise w_n. The bottom-right panel shows the noise, $u_v(t) - u_f(t)$, to be reduced significantly.

Finally, consider the information presented in the bottom-left panel for vehicles $j = 1, 2, \ldots, n$ where where $n = 20$. The start locations for vehicle j is given by (2) where the vehicles are evenly spaced at start time $t = 0$. Speed forecasts are made following the procedure described in the previous paragraph. In other words, twenty simulations are made; one for each vehicle.

The $t - x$ forecasts may be considered remarkable. All vehicles are forecast to travel without delay at a flow equal to the capacity c. They also travel at headway s^*, thus they travel safely. The group benefits. By preventing queuing from forming, congestion is eliminated. The result is obtained by: (1) tracking $u^*(t)$ from (1) and (2) minimizing process noise w_d and sensor noise w_n.

DISCUSSION

This paper may be considered an academic exercise that solves a toy problem with no practical application. Granted, the *car following algorithm* is limited to explaining delay and analyzing performance under special conditions. However, the importance of traffic noise σ in explaining delay was demonstrated with the aid of SDE models incorporated in the framework of a *car-following algorithm*. The FHA reports that "Fluctuations in Normal Traffic" is one of the seven causes of congestion (Systematics 2005). Linking driver behavior and traffic noise is important. Theoretically, speeders, slow pokes and inattentive drivers should no longer be a problem in the future with feedback control using Kalman filtering. This is a strong claim that requires scrutiny. Consider the following three questions:

How will the feedback control scheme be implemented in practice? The vehicles using feedback control will wirelessly transmit speed data to roadside units that are connected to a central computer. This is a V2X system, which allows vehicles to communicate and share information with devices around them. The central computer will use the feedback control model, the state space model of (9) and (10), analyze the data, and then transmit filtered u_f speed instructions back to the transmitting vehicles. The V2X system measurement data and u_f speed forecasts will be tagged so each vehicle will be individually controlled.

V2X drivers will steer their vehicles but feedback control will be used to control speeds. Under this system, V2X vehicles operate as Level One autonomy vehicles. They act in a manner similar to adaptive cruise control (ACC) vehicles that sense slowing traffic to avoid crashing.

What are the shortcomings of the feedback control system using Kalman filtering? The V2X system has not been tested in the field. The results presented in the paper have relied on simulation. The results are promising as illustrated by the $t - x$ trajectories given in the lower-left panel of Figure 5. The next step in a traditional validation approach is to conduct an operational or field test and then develop specifications for building an operational system. Obviously, this is a cautious procedure that assures success. Field testing will confirm whether or not the feedback control system is effective as the simulation results predict.

The field experiments conducted by the research teams of Sugiyama et al. (2008), Tadaki et al. (2013) and Stern et al. (2018) showed the importance of traffic noise. The stochastic car following models are designed to mimic the conditions observed in the "ring road" experiments as closely as possible. For example, all vehicles in the field tests were evenly spaced and all drivers were carefully trained to maintain a constant speed and to minimize of speed fluctuation. Stern's team used an air horn that first commanded all drivers to "switch gears from Park to Drive" and next to "begin driving" on a second command. The field tests should assure that this condition is met.

The field test should also investigate the effects of uneven vehicle spacing at start time $t = 0$. Instead of treating the spacing s^* as a constant in establishing the starting locations $x_j^*(0)$ of (2) as a constant, treat it as a random variable such that $X_j^*(0) = (j-1)S$ where S is a random variable of headway. This test will provide information about the robustness of the feedback control system.

Is a V2X system a practical tool for the future? The feedback control system presented in this paper and envisioned for the future should be welcomed in a "smart city," a city where different types of sensors (IoT devices) are used for data collection and to efficiently manage resources for a wide variety of operations including roadways. The research and development costs of a V2X system are difficult to estimate but the costs associated with doing nothing are high. For New York State, for example, "The combination of rough roads and congestion costs motorists a total of \$6.3 billion statewide — that's \$694 per driver in NYC, \$504 for Albany, and \$477 for Syracuse" (ASCE 2017). This is a strong economic argument for change.

The look and feel of the V2X system with its central computer and roadside connection devices may give the public that it falls in the class of an autonomous vehicle (AV). Implementing AVs at Level Five, fully with no human control, will require cultural change. Some critics argue the public may reject them. Fortunately, since the V2X system offers congestion relief at Level One, its fate may be welcomed.

SUMMARY

A mechanistic-modeling approach is used to simulate conditions observed in a "ring road" experiment. Drivers drove around a single-lane circular roadway that restricted them from passing. The distance between their vehicles was relatively close so traffic density was a factor in the experiment. All drivers promised to maintain a constant speed but could not. Small perturbations in speed, called *traffic noise*, were observed and shortly after the initiation of the experiment. Moving queues formed. The combination of traffic noise and high traffic density strongly suggest it to be the cause of traffic breakdown.

To explain moving queue formation, a stochastic car following model was developed. It consists of stochastic differential equation models, Brownian motion models, to simulate driver behavior. Since individual drivers were unable to maintain constant speeds, they were also unable to maintain constant space headways between their vehicles. Vehicle clusters formed. They forced drivers to decelerate to avoid crashing. The stochastic car following model revealed that vehicle interaction is complicated and impossible to forecast. However, the model proved to be effective in simulating and explaining queue formation.

As with most simulation models, model parameter calibration is an issue. Traffic noise used in the stochastic car following model is assumed to be a normal probability distribution. An investigation of the standard deviation in speed found it to be relatively small in relation to the mean vehicle speed, ranging from one to three percent.

A feedback control model was developed that demonstrates its potential in preventing traffic delay and breakdown. The potential for using feedback control in a "smart city" environment was critically assessed and its fate 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 2019).

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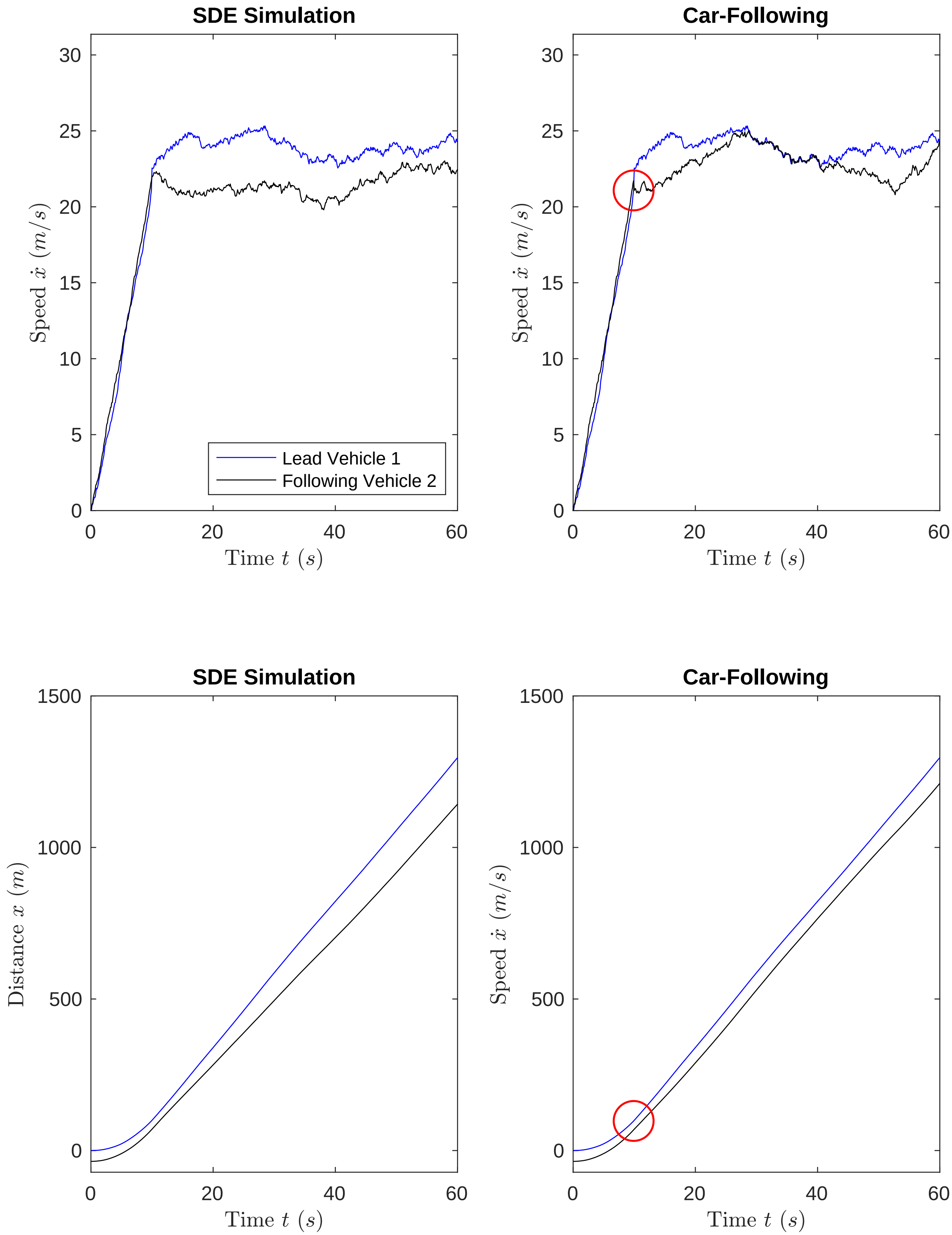
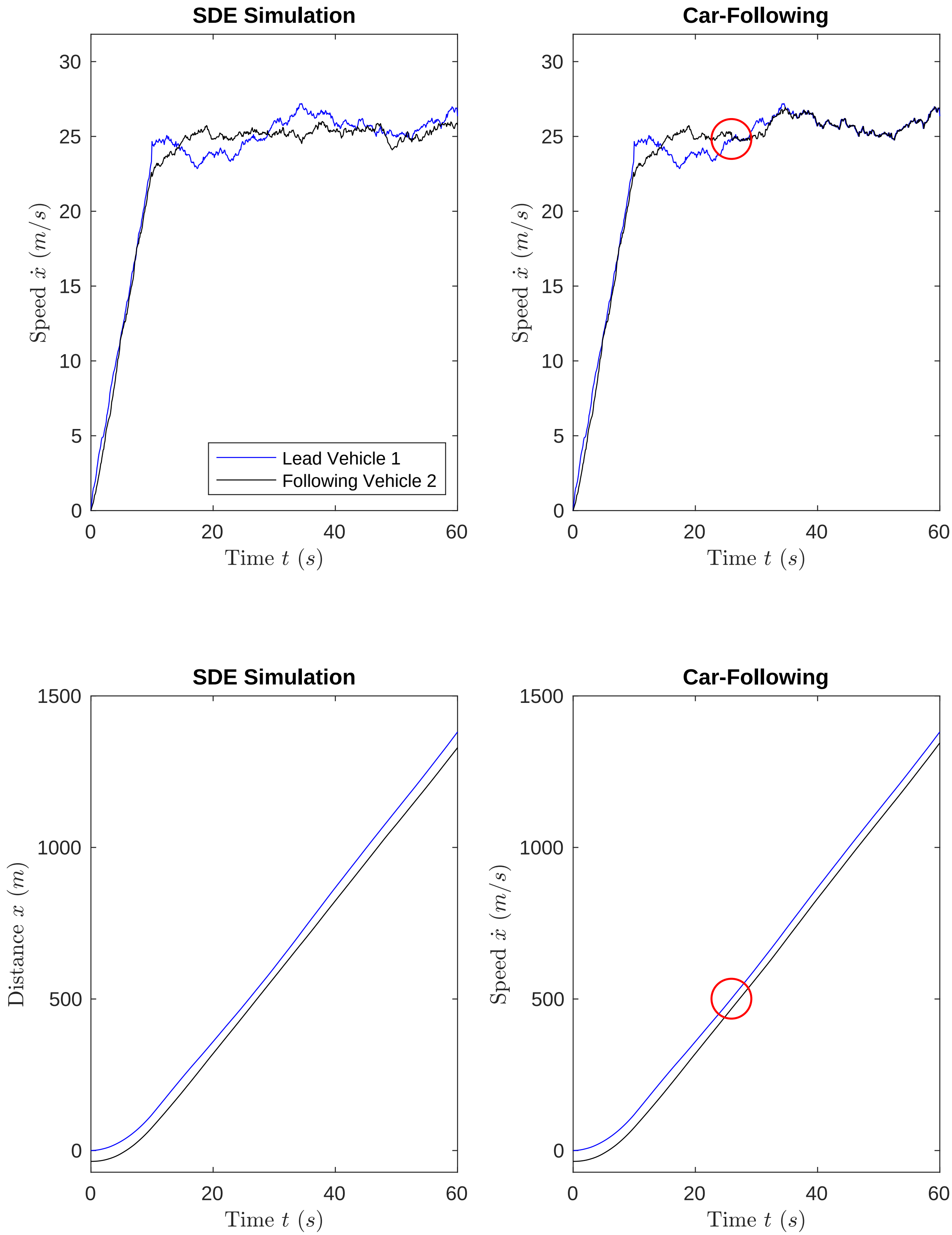
Noise σ/u^*	Seed	Time t (s)	Speed $\bar{u}$ (km/h)	Density k (pc/km)	Flow q (pc/h)	Moving Queue	$s(t) < s^*$ Violation Average
0%	125	10	84.5	28.0	2370	No	0
		30	85.3	28.0	2390		
		60	85.3	28.0	2390		
0.05%	125	10	84.3	27.8	2344	No	370
		30	81.7	27.0	2210		
		60	85.9	24.7	2120		
1%	125	10	84.3	27.7	2340	Yes	269
		30	77.1	26.3	2030		
		60	77.1	20.8	1600		
1.5%	125	10	84.3	27.5	2320	Yes	215
		30	73.4	25.0	1840		
		60	68.9	17.6	1210		
1.5%	127	10	84.3	28.8	2420	Yes	232
		30	70.5	27.5	1940		
		60	84.3	23.8	2010		
3%	125	10	84.2	27.0	2370	No	147
		30	60.3	22.3	1350		
		60	44.1	11.6	510		

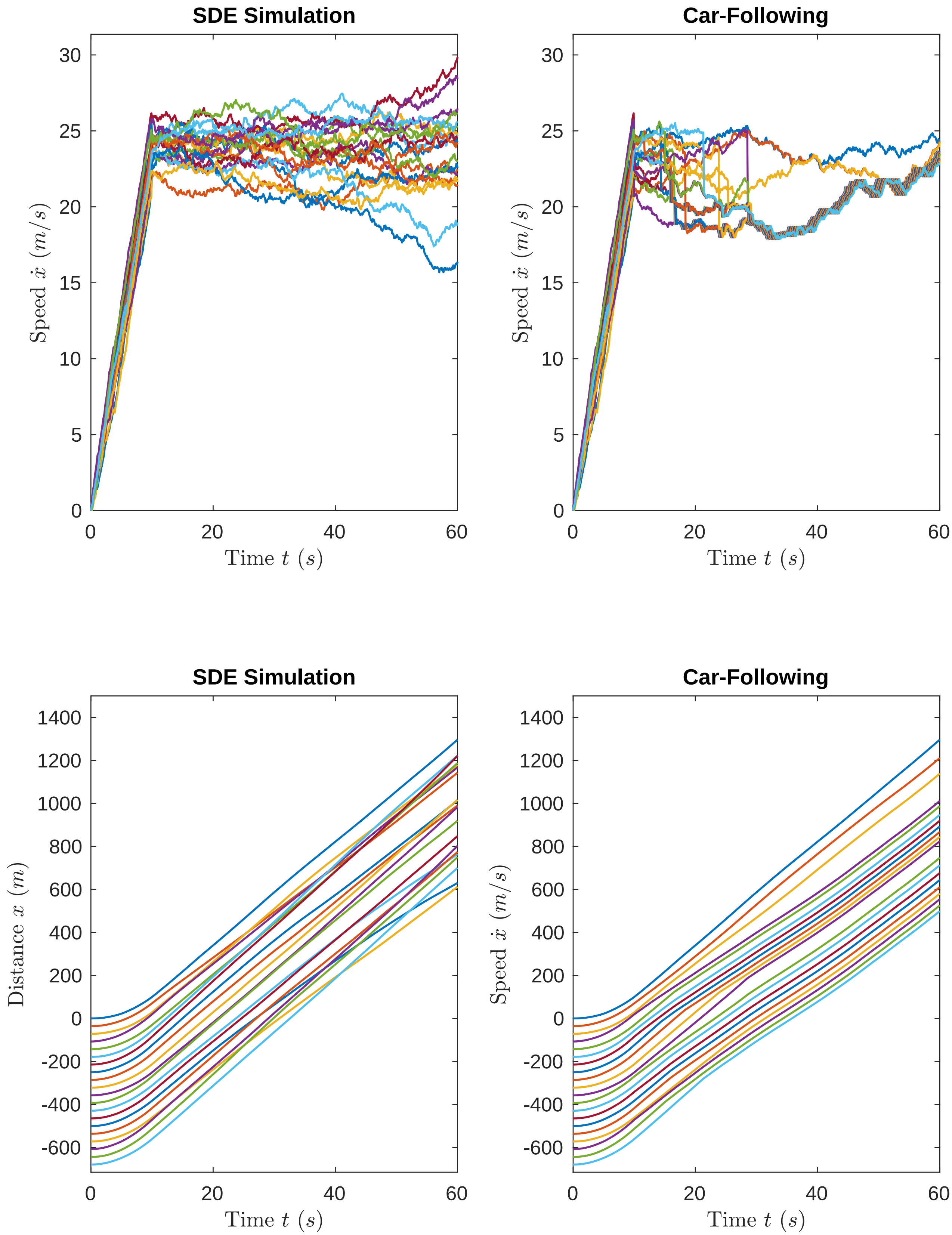
TABLE 1. Performance Estimates.

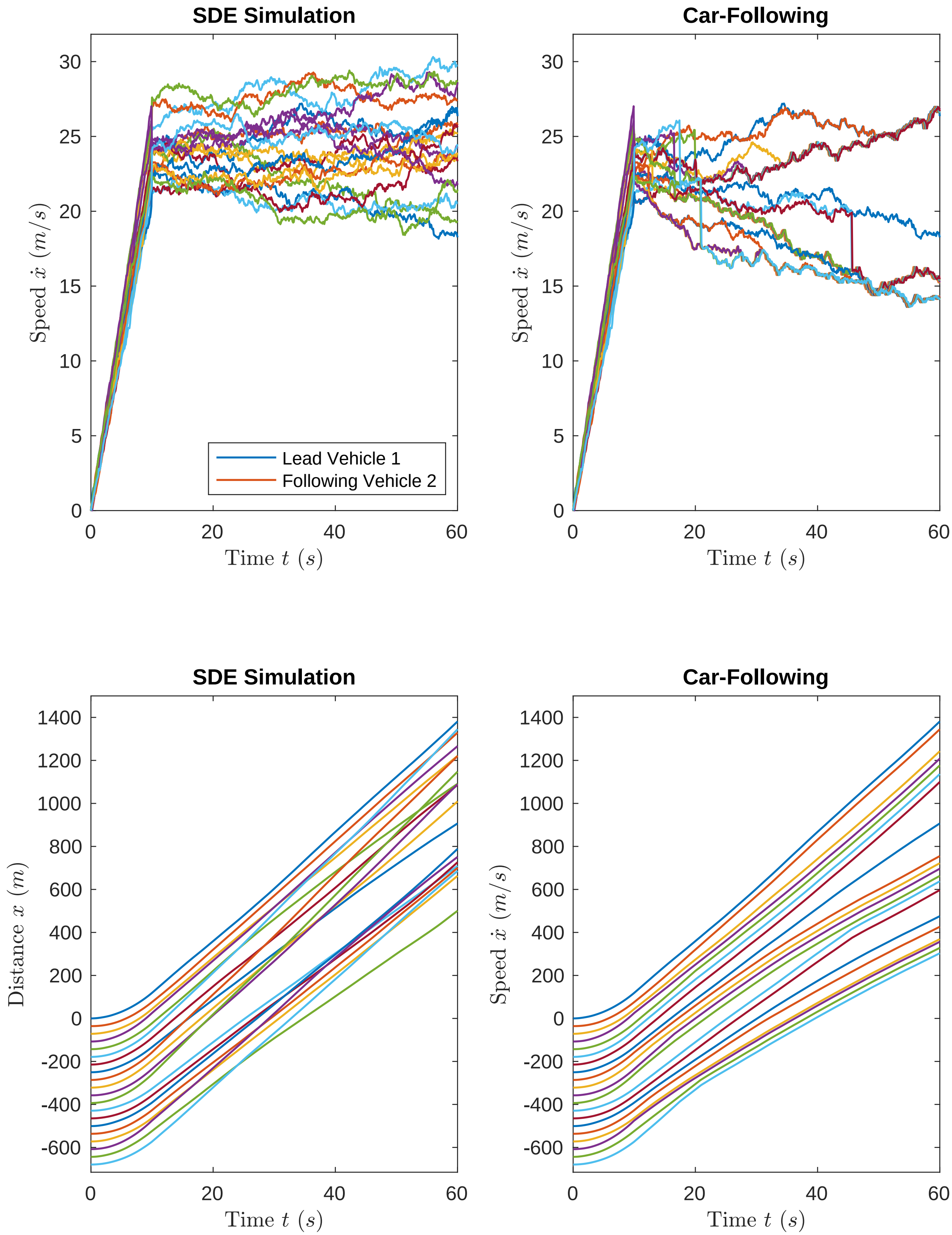
Figure

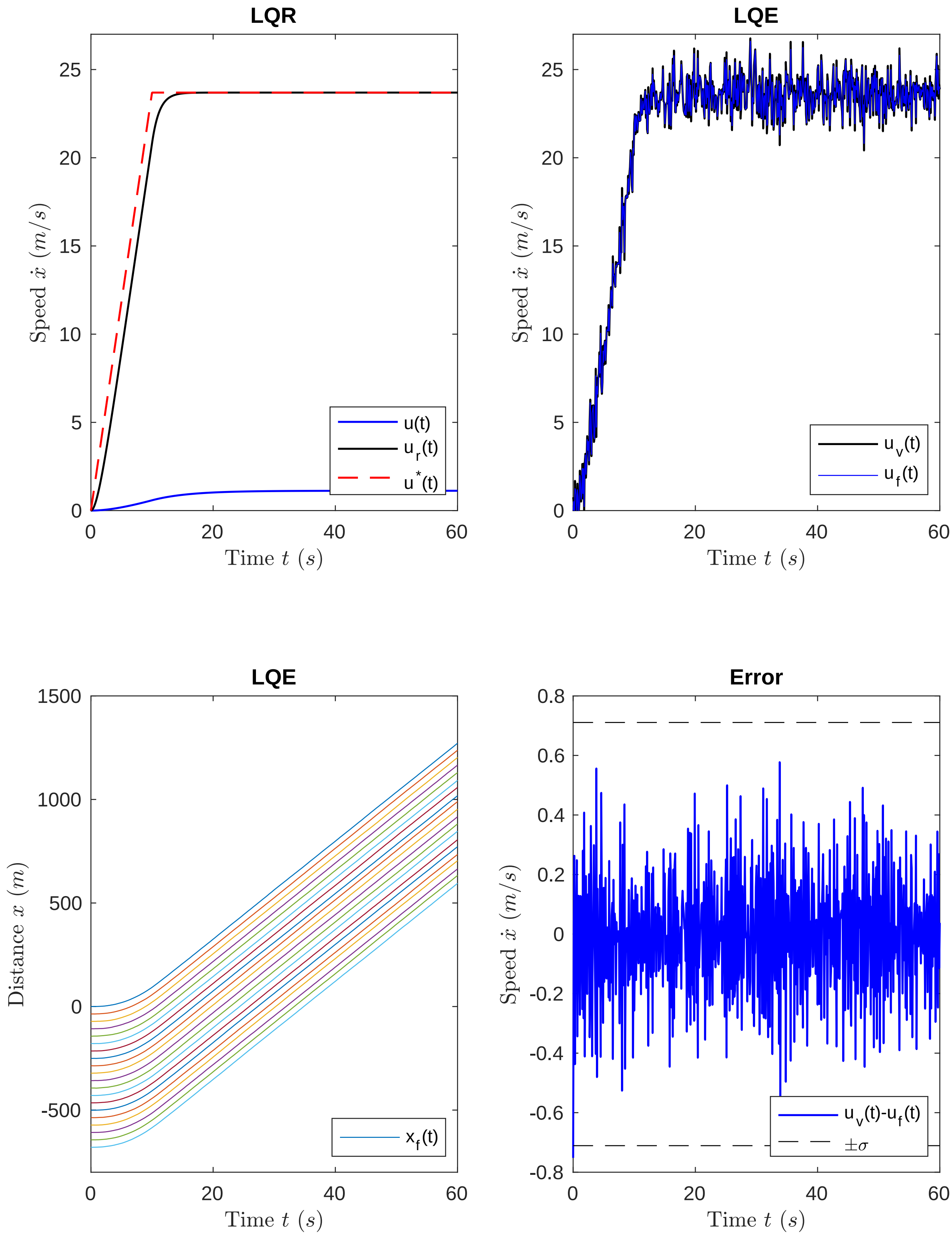


SDE Simulation
Car-Following
Speed $\dot{x}$ (m/s)
Time t (s)
Lead Vehicle 1
Following Vehicle 2
0
5
10
15
20
25
30
40
60
SDE Simulation
Car-Following
Distance x (m)
Speed $\dot{x}$ (m/s)
Time t (s)
500
1000
1500


SDE Simulation
Car-Following
30
25
20
15
10
5
0
Speed $\dot{x}$ (m/s)
Lead Vehicle 1
Following Vehicle 2
0
20
40
60
Time t (s)
SDE Simulation
Car-Following
1500
1000
500
0
Distance x (m)
Speed $\dot{x}$ (m/s)
Time t (s)


SDE Simulation
Car-Following
Speed $\dot{x}$ (m/s)
Time t (s)
0
5
10
15
20
25
30
0
20
40
60
SDE Simulation
Car-Following
Distance x (m)
Speed $\dot{x}$ (m/s)
Time t (s)
1400
1200
1000
800
600
400
200
0
-200
-400
-600


SDE Simulation
Car-Following
Speed $\dot{x}$ (m/s)
Time t (s)
Lead Vehicle 1
Following Vehicle 2
30
25
20
15
10
5
0
0
20
40
60
SDE Simulation
Car-Following
Distance x (m)
Speed $\dot{x}$ (m/s)
1400
1200
1000
800
600
400
200
-200
-400
-600



LQR
Speed $\dot{x}$ (m/s)
Time t (s)
u(t)
u_r(t)
u^*(t)
LQE
Speed $\dot{x}$ (m/s)
Time t (s)
u_v(t)
u_f(t)
LQE
Distance x (m)
Time t (s)
x_f(t)
Error
Speed $\dot{x}$ (m/s)
Time t (s)
u_v(t)-u_f(t)
$\pm\sigma$

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Reviewer #1: *The present study proposed a feedback control strategy to demonstrate that equipped vehicles could be used to address speed perturbations in vehicle platoons. The writing is easy to understand, and the methodology is solid. However, the author did not provide enough and clear details, and the organization of the paper is not logically smooth. In addition, it lacks a review of existing studies. More importantly, the same problem addressed in the paper has been extensively studied in existing studies. The research gap and contribution of the present study is not clearly stated. Detailed comments are shown as follows:*

1. *In the abstract, the author claimed that a field experiment was conducted. However, this paper only conducted numerical simulations. I guess the author refers to the work of Suyiyama et. al. The abstract should be revised to avoid confusion.*

The **ABSTRACT** has been rewritten to address issue and to more clearly outline the goals of this paper on simulation.

2. *As a technical paper, the present study lacks a review of existing studies. A literature review should provide readers the state-of-the-art of studies in related areas, and also demonstrates that the authors are familiar with the research topic.*

A more comprehensive literature review has been conducted. See lines 62 though 103 in the **METHODS** section.

3. *In the introduction, the author proposed a pivotal question that whether equipped vehicles could prevent moving queues and extra delays. However, this problem has been extensively addressed via various approaches, and the answer is yes according to most existing studies. Since the Suyiyama's research is the building block of the current paper, I strongly recommend the author to read the following paper listed as follow:*

Stern, R. E., Cui, S., Delle Monache, M. L., Bhadani, R., Bunting, M., Churchill, M., ... & Seibold, B. (2018). Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments. Transportation Research Part C: Emerging Technologies, 89, 205-221.

This paper demonstrates that even with a low penetration rate, equipped vehicles could improve the performance of traffic flow and dissipate stop-and-go waves, or traffic volatility, according to the terminology of this study. The study of Stern et.al. also use feedback control methods and they demonstrate the proposed control strategy through filed experiments.

I appreciate the reviewer's comment. This paper and another paper on field experiment by Tadiki have been added to the **METHODS** section, line 60, and the **DISCUSSION** section, lines 363 through 370.

4. *Line 55, the author mentioned that the target values are set up according to HCM, please provide specifics. It seems like only the q=ku function is used.*

This issue has been addressed. See subsection of *Traffic Performance* in **METHODS**, lines 216 through 220.

5. *Please provide explanations to the notations of the lower panel of Fig. 1.*

The sample size has been increased from 4 to 20 vehicles, therefore the original paper has been revised and all figures in the paper have been replaced.

6. *Is it necessary to use the drag force as an input? I do not think that the air density is relevant to the current study. Therefore, I recommend using accelerate or velocity instead as inputs for simplification.*

I appreciate the reviewer's comment. The development of the state space model has been rewritten. See lines 287 though 320, equations (7) and (8), equations (9) and (10) and Figure 5.

7. *Line 119, the optimal control law of LQR controllers usually can be found with analytical equations, even when the problem formulation has constraints. The author claim that the "a comfortable acceleration rate is found by trial and error" is questionable and not rigorous for scientific research.*

"trial and error" was a poor choice of words. I added a *Model Calibration* subsection. See lines 259 through 275.

8. *Usually, it takes more than four vehicles to see traffic oscillations clearly. As to the graphical clutter, the author could present figures with a low resolution rather than show all vehicles. Therefore, I recommend the author revise the experiment to include more vehicles.*

The experiment has been revised. The sample size is 20 vehicles. See Figures 3, 4 and 5.

9. *How safe values are calculated in Table 1?*

This issue has been addressed. See *Stochastic Car-Following Models*, lines 163 through 171.

Reviewer #2: *The technical paper presents a feedback velocity control of cars participating in a ring-road experiment. The paper evaluates macroscopic traffic flow quantities of the controlled system. The motivation and contribution of the paper are clear; however the methods and analysis parts are hard to follow. The reviewer believes the paper could be greatly improved if the author(s) could address some major issues.*

Note the list is ordered by the time it appears in the paper, not by its importance.

1. The abstract of the paper shall be better structured, including some conclusions too.

The **ABSTRACT** has been rewritten. I address the issue, "including some conclusions too." See lines 20 and 24.

2. *The first few sentences of the abstract are misleading, as the "field experiment" was not conducted in this paper but used as a reference in this work.*

The **ABSTRACT** has been rewritten to address this issue and to more clearly outline the goals of this paper on simulation.

3. *The control design related parts of the paper are not clearly articulated.*

I addressed this issue by restructuring the paper. The **METHODS** section is divided into two distinct parts: **1. Explaining Breakdown** and **2. Preventing Breakdown**. See lines 286 through 333. It deals with control.

4. *In the Introduction section the sentence "By controlling speed u, it is sufficient to control s* and k*, to minimize the perturbations in speed, and to prevent delay." State what the control inputs and performance outputs are.*
In Line 87, is that a Kalman filter? It is just the state-space representation of a linear system.

I addressed this issue. See equation set (7) and (8) and equation set (9) and (10).

5. *In Line 90, x and u are vectors.*

I removed the **NOMENCLATURE** section and defined the variables in the body of the paper. See See equation set (5) and (6) for example.

6. *Eq. (3) is incorrect. The unit of the left-hand side is acceleration. On the right-hand side, the term -f_d/m*x' has force*velocity/mass (~power) unit.*

This embarrassing oversight is corrected. See lines 296 through 301.

7. *The Car-Following Algorithm section (Line 208) is presenting the results of the numerical simulation, not explaining the model itself.*

The *Stochastic Car-Following Models* subsection explains driver behavior. The material in lines 182 through 188 describes how a driver in a following vehicle reacts to driving too fast or too close to a lead vehicle.

8. *If I understood correctly, there are 4 vehicles in the ring-road experiment experiment.*

It is questionable, how realistic the results are if the sequence of the 4 drivers is repeated.

The sample size has been increased from 4 to 20 vehicles, therefore the original paper has been revised and all figures in the paper have been replaced. Lines 224 through 240 deals with the repeatability issue.

9. *Describe how the Kalman Filter was designed.*

See lines 280 through 320.

10. *The algorithm claims eliminating delay. Yet, there are no figures supporting this claim.*

The *Feedback Control* subsection and Figure 5 deals with this issue.

Editor:

I appreciate the editor's decision to give me the opportunity to address the reviewer's concerns.

The reviewers had valid concerns but neither reviewer addressed the **DISCUSSION** or **SUMMARY** material in my original submittal. Nonetheless, I feel that it is important to address how my theoretical paper that focuses upon ``traffic noise'' can have practical value. I rewrote the **DISCUSSION** section where I take a critical look at both theory and practice. The **SUMMARY** was also revised.