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Procedia
Social and Behavioral Sciences

Procedia - Social and Behavioral Sciences 00 (2013) 000–000

www.elsevier.com/locate/procedia

Conference on Agent-Based Modeling in Transportation Planning and Operations

Autonomous traffic-jam clearance using a frugal adaptive cruise control strategy

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Abstract

Traffic congestion is one of the most important issues to be addressed in transport management. Since building new transport infrastructure is no longer an appropriate option in many regions, strategies need to be sought to arrange traffic in a more efficient manner. A device that suggests itself for this purpose and that is already available in many vehicles is adaptive cruise control. Adaptive cruise control is a device that automatically regulates vehicle acceleration according to desired speed and distance to the front vehicle. It is obvious that such a device can be actively used to help arranging vehicles more efficiently and minimize congestion. With this in mind, scholars have suggested to actively attune some of the driver's ACC settings to the current traffic situation when it becomes critical. Previous work in this direction, however, proposed strategies that relied on static and imposed classifications of traffic situations and static and imposed setting adjustments. Although the effectiveness of such strategies could be proven for a particular record once the classifications and setting adjustments were calibrated, it remains unclear whether these strategies also work in other settings. In this study, we propose a novel ACC-assisted driving strategy that attunes ACC parameters in an individual and dynamic way and on a continuous scale. The goal was to create a strategy that is frugal but yet effective across different types of traffic situations. In this study, we compare the proposed strategy with a classification-based one for a closed two-lane freeway system with an on-ramp via simulations. We could show that under the proposed strategy traffic speed could be increased by more than 600 %, stop-and-go patterns could be significantly reduced, but driving comfort significantly increased. In contrast, the tested classification-based strategy was only slightly effective. We conclude that further tests with empirical freeway records are required, but that such an effort could be worthwhile.

Selection and/or peer-review under responsibility of Chinese Overseas Transportation Association (COTA).

Keywords: adaptive cruise control; traffic congestion; traffic clearance; agent-based modeling; self-organizing traffic;

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1. Introduction

Traffic congestion is one of the main issues to be addressed by today's traffic management schemes (Baskar et al., 2011). Travel demand is increasing, and the loss of travel time and the huge related societal and economic cost are major but still unsolved problems (Baskar et al., 2011). Though, in most countries, building new transport infrastructure is no longer an appropriate option (Kesting et al., 2006). More effective road usage through intelligent technology is thus one of the major promising opportunities. Current traffic flow management systems already make use of such intelligent technology, including ramp metering, variable speed limits, automated lane closures, shoulder lane openings, etc. In the future, highways may even be designed as so-called Intelligent Highway Systems (IHS) using even more advanced technologies such as adaptive speed limits and dynamic and distributed route guidance (Baskar et al., 2011). Two currently discussed designs for such Intelligent Highways Systems are automated platooning and self-organizing traffic. In automated platooning vehicles are arranged in closely spaced groups called platoons (Broucke and Varaiya, 1997). To avoid collisions, intra-platoon spacing is kept very small using electronic or mechanical coupling while the inter-platoon spacing is kept larger (Li and Ioannou, 2004; Varaiya, 1993). While platooning systems would require large initial investments in special road infrastructure (Kesting et al., 2008), there is already potential for intelligent self-organizing traffic through currently available automated driving assistance in many cars, such as adaptive cruise control (ACC). Such devices would then not only arrange traffic in a collision-free and distributed manner, but also have the potential to organize traffic in a way such that congestion is minimized.

But how could such technology do so? According to the U.S Department of Transportation (2013), almost half of traffic congestion is caused by recurring traffic issues in the United States. Recurring incidents, as opposed to non-recurring incidents (e.g. adverse weather, special events, or lane closures), are those events that regularly occur, comprising bottlenecks and excessive demand (e.g. in rush hours) (Downs, 2004). Regarding the latter, it was argued in previous studies that excessive demand has a non-linear effect on traffic flow, i.e. that phase transitions from free and bound traffic flow to stop-and-go traffic jam occur when demand exceeds thresholds (e.g. Davis, 2012; Lee and Kim, 2011). In other words, when vehicle densities are gradually increasing, traffic flow can withstand these increases once densities are low, and quickly breaks down when vehicle densities further increase. This non-linearity suggests that this reaction is rather a consequence of the disorganization of traffic induced by the increased traffic density than of the traffic-density increase itself. This observation prompts the idea that intelligent harmonization of traffic can potentially stabilize the phase of bound traffic flow against increases in vehicle density, and that such harmonization can be achieved via self-organizing vehicles and intelligent technology.

An existing device that already suggests itself for this purpose is adaptive cruise control (ACC), which is a sensor-based device that sets acceleration to achieve a desired speed, while maintaining a minimum headway distance to the preceding vehicle. However, it is currently not clear whether existing ACC use reduces traffic congestion or even impedes traffic flow. While some investigations predict a positive effect of ACC (e.g. Treiber and Helbing, 2001; Davis, 2004), others are more pessimistic (Kerner, 2004; Marsden et al., 2001, cited from Kesting et al., 2008). As a resort to this debate and to the related potential shortcomings of ACC, Kesting et al. (2008) suggested instead to find ways to actively set the parameters of the vehicle ACC system such that traffic stability is increased and jams potentially cleared. Accordingly, Kesting et al. (2008) proposed to slightly modify ACC parameters as set by the driver, depending on the particular local traffic situation of the vehicle. To test this strategy, Kesting et al. (2008) defined five discrete traffic situations for a case-study record from a section of the German-Austrian autobahn A8 with an on-ramp bottleneck, and determined parameter value adjustments for each situation. The parameter value adjustment strategy largely followed a simple jam-dispersion strategy of letting vehicles approach the traffic front more slowly while letting them leave the traffic front faster. With simulations, the authors could show that an equipment level of 25 % ACC vehicles could completely eliminate traffic congestion for their recorded setting (Kesting et al., 2008).

However, it is unclear whether the ACC-based strategy proposed by Kesting et al. (2008) also works for other case studies than the particular case study it was calibrated for. For instance, the braking and acceleration calibrated for this case study could disperse a traffic front excessively in other settings, leading to undesirable accordion effects elsewhere along the motorway. Similarly, we suspect that phase changes are too complex and variable to be defined by a set of static traffic-situation classes. In this paper, we therefore propose an ACC-based strategy that works without classification and static rules, but with dynamic acceleration adjustments that are adapted individually and on a continuous scale. The goal is to compare the effectiveness of the ACC-based strategy by Kesting et al. (2008) with ours with regard to traffic flow and driving comfort. In order to compare them, we developed a discretized agent-based version of the microscopic model by Kesting et al. (2008) for a closed two-lane freeway setting, and conducted simulations for different traffic situations. In Chapter 2, we will present the components of the model, the two ACC-based strategies to be compared, and how the components/alternatives were implemented. In Chapter 3, we will present and analyze simulations results, based on indicators for driving comfort, speed and stop-and-go dynamics. A discussion is given at the end of the study.

2. Materials and methods

Kesting et al. (2008) conducted their multiple-lane simulations via a continuous microscopic model, calibrated to match an empirical record from a section of the German autobahn A8. The model consists of three components, the single-lane car-following model by Treiber (2000), the lane-change model MOBIL by Kesting et al. (2007) to be able to model multiple-lane traffic, and the ACC-based strategy proposed by Kesting et al. (2008). In what follows are summaries of these three components, followed by a presentation of our own proposed ACC-based strategy, and a description of the agent-based implementation of Kesting et al.'s model with which the two ACC-based strategies can be tested.

2.1. Car-following model

Kesting et al. (2008) modeled both human and ACC-assisted driving with the same model, i. e. the Intelligent Driver Model (IDM) by Treiber (2000). Currently, there are already vehicles equipped with an ACC system, which includes radar or infrared sensors that enable the system to sense the distance and speed difference to the preceding vehicle (Marsden, 2001). In ACC-assisted driving, the vehicle is generally made to reach and maintain a certain speed preset by the driver, while the car maintains a minimum safe time gap to the front car as preset by the driver as well. The ACC system does so by adjusting the vehicle's acceleration or deceleration in response to the traffic situation and the driver's settings. The Intelligent Driver Model is able to give a natural description of both human and ACC-based driving. In particular, it sets the acceleration $\dot{v}$ (m/s²) equal to the free-flow acceleration for reaching the desired speed v_0 (km/h), minus a braking term which becomes dominant when the preceding vehicle gets close, i.e. if the current gap s (meters) to the preceding vehicle becomes smaller than an 'effective desired minimum gap' $s^*(v, \Delta v)$ (equations 1 and 2).

$$\dot{v}(s, v, \Delta v) = a\left[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*(v, \Delta v)}{s}\right)^2\right] \tag{1}$$

where v is the velocity of the vehicle (km /h), Δv the velocity difference to the preceding vehicle, s the current time gap (seconds), and a the maximum acceleration (m/s²).

$$s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \tag{2}$$

where s_0 is the minimum distance in congested traffic (meters), T the safe time gap as preferred by the driver (seconds), and b the comfortable deceleration (m/s²), i.e. the braking intensity perceived as comfortable by the driver.

To summarize, the model parameters that are set according to driver preferences thus comprise the maximum acceleration a (m/s²), the safe time gap T (seconds), the comfortable deceleration b (m/s²), the desired speed v_0 (km/h), and the minimum distance in congested traffic s_0 (meters).

2.2. Lane-change model

In order to simulate traffic on multiple lanes, the above car-following model needs to be complemented with a lane-change model. Kesting et al. (2008) used the lane-change model MOBIL by Kesting et al. (2007) that was specifically designed to complement common car-following models such as the IDM. MOBIL allows two modes of lane change, i.e. symmetric passing as practiced in the U.S., i.e. that overtaking is allowed from both sides, and asymmetric passing as practiced in Europe, i.e. that overtaking is only allowed from the right or left side, depending on country regulations. Since we only consider the U.S. case in this article, we only present the model for the symmetric case.

The general idea is that for a driver both a safety criterion and an incentive criterion to change the lane must be satisfied. The safety criterion is simply that changing the lane is only allowed if the potential new follower would not have to brake too abruptly. In mathematical terms: if $\tilde{a}_n \geq -b_{safe}$, where $\tilde{a}_n$ is the acceleration (in m/s²) of the new follower after a lane change, and b_{safe} is the critical deceleration. The incentive criterion then measures whether a lane change would be beneficial, using a utility measure. This utility depends on the potential speed gain/loss following a lane change, and on the potential speed gains/losses of the current and the new follower, here expressed in terms of their acceleration (equation 3). A parameter p between 0 and 1 determines the politeness of the driver, regulating to what degree the driver considers the others' gains/losses.

$$\tilde{a_c} - a_c + p\left(\tilde{a_n} - a_n + \tilde{a_o} - a_o\right) > \Delta a_{th} \tag{3}$$

where a_c, a_n, and a_o are the current acceleration (in m/s²) of the vehicle, of the new follower, and of the old follower, respectively. A tilde denotes the particular acceleration of the vehicles after the lane change. Δa_{th} is the utility threshold beyond which a lane change is beneficial (which we set to 0). Drivers constantly evaluate the side lanes in terms of this utility. When the utility is above the threshold, they instantly change to the respective lane. If the utility is above the threshold for the right and the left lane (i.e. in case of a middle lane), the driver switches to the lane with the higher utility.

2.3. ACC-based strategy by Kesting et al. (2008)

The last component of the model by Kesting et al. (2008) consists of a traffic assistance system in which vehicles automatically adapt some of the above ACC parameters according to the local traffic situation, with the goal to improve both traffic flow and driving comfort. The ACC parameters that are being adapted comprise the maximum acceleration a, the comfortable deceleration b and the safe time gap T (the remaining parameters of the ACC system, the desired speed v_0 and the minimum distance in congested traffic s_0, remain unchanged). For the traffic situation assignment, Kesting et al. (2008) defined five typical traffic situation classes for their case setting, which was a freeway section including an on-ramp. These classes included free traffic, upstream jam front, congested traffic, downstream jam front, and the on-ramp bottleneck section. The authors then proposed that the vehicles should adjust the three parameters depending on the particular traffic situation the vehicle is currently in (see equation 4 and Table 1). For the particular definitions and detection algorithms of these classes we would like to refer to the original article (Kesting et al. 2008).

$$a^{(s)} = \lambda_a^{(s)} a, \quad b^{(s)} = \lambda_b^{(s)} b, \quad T^{(s)} = \lambda_T^{(s)} T \tag{4}$$

where $a^{(s)}$, $b^{(s)}$ and $T^{(s)}$ are the parameter values at point of time s, and the lambda are factors depending on the situation class at point of time s (see Table 1).

Table 1: Parameters settings of the ACC driving strategy: reprinted from Kesting et al. (2008).

Traffic situation	λ_T	λ_a	λ_b	Driving behavior
Free traffic	1	1	1	Default/comfort
Upstream front	1	1	0.7	Increased safety
Congested traffic	1	1	1	Default/comfort
Bottleneck	0.5	1.5	1	Breakdown prevention
Downstream front	0.5	2	1	High dynamic capacity

The general idea behind this proposed strategy is to disperse congested traffic by approaching traffic fronts more slowly and leaving them faster and in a denser fashion. In bottleneck sections, faster and more dense traffic is supposed to increase road capacity and thus traffic flow. Kesting et al. (2008) could show that for empirical detector data of a section of the German autobahn A8 both comfort and traffic flow could be improved with this ACC-based strategy.

2.4. Proposed ACC-based strategy

It remains unclear whether the above-described strategy was particularly designed to dissolve recorded traffic congestion in the recorded section, or whether it also works for other settings. We suspect that while such very specific assignments of values may work in one traffic situation and infrastructural setting, it may not work for others. For instance, the strategy may cause a too strong dispersal of congested traffic and accordion effects in other sections of a freeway when the strategy is not calibrated to the particular traffic and infrastructure of a section. In particular, we believe that the improvement of traffic flow and driving comfort in other settings require different classifications of traffic situations and different parameter values.

We therefore suggest to approach the problem from a distributed intelligence viewpoint; each vehicle should continuously adjust its acceleration based on local information until overall traffic is dispersed in an emergent manner. Thereby, the algorithm should at best be simple and free from an imposed classification of traffic situations and rules. Motivated by these thoughts, we propose a simple strategy, which consists of only adjusting the acceleration of a vehicle when it comes close to the preceding vehicle. In particular, we propose to then set the acceleration of the approaching vehicle proportionally to the speed difference to the preceding vehicle (equation 5). This implies that the faster the approaching vehicle is, relative to the preceding vehicle, the stronger is its reaction in terms of deceleration (and vice versa). But, as mentioned above, such a reaction should only be triggered under the condition that the approaching vehicle comes close, which is expressed in terms of distance to and average speed of the front vehicle (equation 5). This way, this threshold is dynamic and individual, and not static and externally defined. When this condition is not met, the vehicle runs at its normal acceleration as calculated by the ACC (equation 1).

$$\texttt{If}\ (dist^p \leq v^p_{mean} + c) \Longrightarrow \ \dot{v} \mapsto \gamma \cdot (-\Delta v) \tag{5}$$

where $dist^p$ is the current distance to the preceding vehicle in meters, v^p_{mean} the average distance to the preceding vehicle over a passed time period, c a constant, Δv the speed of the vehicle minus the speed of the preceding vehicle, and γ the intensity of the deceleration/acceleration reaction. Thereby, it is assumed that the ACC system is endowed with a memory that can record past values. Let, in this respect, be M the number of entries along the past that can be recorded until presence, and that older values are replaced by newer ones. We can therefore define v^p_{mean} as the arithmetic mean over these M entries.

The basic idea behind this algorithm (equation 5) is that before stop-and-go accordion effects emerge and lead to collapse of traffic flow, vehicles should start breaking earlier and more strongly when such stop-and-go fronts start emerging ahead of them. The idea is similar to the one by Kesting et al. (2008), but works on a frugal continuous basis instead of a probably case-sensitive set of discrete situation classes and static reaction rules. It is to be tested whether the proposed algorithm works in acceleration dimensions feasible for a vehicle, whether the braking maneuvers decrease or even increase comfort of driving, and whether traffic can be held stable against stop-and-go accordion effects.

2.5. Agent-based implementation

We developed an agent-based model in NetLogo 4.0.5. (Wilensky, 1999) that implements the car-following model IDM, the lane-change model MOBIL and the two ACC-based strategies as alternatives. It may not matter whether agent-based modelling (ABM) or microscopic modelling is used, but we selected ABM since we are more familiar with this modeling approach. The agent-based model is a discretized version of the one by Kesting et al. (2008), with a sufficiently small time step interval of 0.05 seconds – sufficient in terms of resolution required for the car-following model to work. The infrastructural setting, however, is different from the one by Kesting et al. (2008). Since we are interested in testing whether the proposed strategy has in general the power to arrange traffic such that accordion effects dissolve globally, we decided to do a first pre-test in this article on a closed system, in this case a circular freeway. We endowed this freeway, which we gave a length of 1400 m, with two lanes and an on-ramp of length 300 m.

To initialize the model, Num_{veh} (see Table 2) vehicle agents are created, thereby only representing passenger cars, and randomly distributed over the freeway. Driver preferences and ACC settings (Table 2), as required for the models above, are initialized. In order to initialize the components that we adopted from Kesting et al. (2008), we proposed parameter ranges varying around typical values as suggested by Kesting et al. (2008) (Table 2, first section). Since Kesting et al. (2008) did not provide IDM parameter values that can represent human driving behavior, we decided, for the time being, to only consider ACC-based driving in the model. Reasonable ranges for the newly introduced parameters (Table 2, second section) were identified by test simulations. During model initialization, also the behavior of vehicles advancing from the on-ramp is initialized. These include the probability of new vehicles appearing from the on-ramp in a time step, the maximum vehicles then appearing, and the degree to which appearing vehicles adopt the average speed of local traffic (Table 2, last section).

After initialization, the following time loop of procedures is run in every time step:

1. Calculate the velocity v for each vehicle from the acceleration $\dot{v}$ and the velocity in the previous time step.
2. Translate this velocity in a forward motion of vehicles along the highway.
3. Let new cars enter the system via the on-ramp according to settings in Table 2.
4. Calculate for each vehicle the accelerations of surrounding vehicles with and without a lane change of the vehicle (needed for step 6).
5. Calculate the own acceleration for each vehicle according to the selected alternative (without ACC-assisted strategy (section 2.1), with the ACC-assisted strategy by Kesting et al. (2008) (section 2.3), or with the proposed one (section 2.4).
6. Each vehicles decides whether to change lane (according to section 2.2).

Table 2: Model parameters

Variable	Meaning	Reasonable range	Unit
Driver and ACC settings for original model components			
v_0-mean	Average desired speed of drivers	100 - 140	km/h
v_0-std	Standard deviation of desired speed among drivers	0 - 20	km/h
T-mean	Average safe time gap desired by drivers	1 - 2	seconds
T-std	Standard deviation of desired safe time gap among drivers	0 - 0.4	seconds
s_0-mean	Average desired jam distance of drivers	1 - 3	meters
s_0-std	Standard deviation of desired jam distance among drivers	0 - 1	meters
a-mean	Average maximum acceleration of drivers	1 - 1.8	m/s^2
a-std	Standard deviation of maximum acceleration among drivers	0 - 0.4	m/s^2
b-mean	Average comfortable deceleration of drivers	1 - 1.8	m/s^2
b-std	Standard deviation of comfortable deceleration among drivers	0 - 0.4	m/s^2
p-mean	Average politeness index of drivers	0.4 - 0.6	——
p-std	Standard deviation of politeness index among drivers	0 - 0.2	——
Newly introduced ACC settings			
M	ACC memory length (i.e. number of values to be saved)	100 - 300	——
c	Constant (equation 5)	5 - 15	m
γ	Reaction intensity (equation 5)	5 - 15	——
General traffic settings			
Num_{veh}	Number of initial vehicles created	5 - 60	—
$Prob_{app}$	Probability of new vehicles appearing from on-ramp	0 - 0.01	/ time step
Max_{app}	Maximum vehicles appearing from on-ramp in one time step	1 - 5	/ time step
$Thwart_{app}$	Degree to which appearing vehicles adopt the average speed of traffic	0 - 1	——

3. Results

In order to compare the effectiveness of the two ACC-based strategies, we created a set of scenarios to be tested, which are described in section 3.1, together with the simulation schedule. The effectiveness of the two strategies is compared on the basis of a set of indicators, which are defined in section 3.2. In section 3.3., the simulation results are presented and analyzed.

3.1. Scenarios and simulation schedule

In order to test whether and to what degree the ACC-based strategies can prevent traffic breakdown in different traffic situations, we first created different scenarios in terms of driver preferences, ACC settings, and general traffic settings (Table 2). The scenarios were created by randomly varying all model parameters in Table 2 within their 'reasonable range' as given in Table 2. Thereby, the driver preferences were generated as values randomly drawn from a normal distribution defined by arithmetic mean and standard deviation, while the purely technical ACC settings were generated based on an equal distribution. Please note that this way not only the values were varied heterogeneously for the vehicles among scenarios, but that the average and the degree of heterogeneity itself was varied. The goal of scenario creation was to be able to compare the two ACC-based strategies with the baseline (i.e. without adaptation of ACC settings) across a wide range of traffic situations. In total, 25 scenarios were created.

We conducted two sets of simulations. In the first set, we gradually increased vehicle density over time via on-ramp traffic, with the purpose to dynamically assess to what extent traffic can be held stable under the ACC-based strategies and the baseline when density increases. Each traffic scenario was simulated 10 times for each of the three alternatives, for a period of 10 000 time steps (= 500 seconds), a period sufficient for the strategies to become effective. The purpose of the second set of simulations was then to analyze the relationship between vehicle density and the effectiveness of the two ACC-based strategies more analytically. For this purpose, the vehicle densities of the scenarios were varied systematically in steps from low to high. For each traffic scenario, alternative, and vehicle density, one simulation run was conducted, again for a period of 10 000 time steps.

3.2. Indicators

During each run, five indicators were produced. The first two indicate to what degree stop-and-go traffic can be dissolved, simply comprising average speed (km/h) and the variation of speed (i.e. the standard deviation) among vehicles (also in km/h) in a time step. The other three indicators measure comfortability of driving. These are comprised of a safety index and two indicators measuring the abruptness of driving.

To calculate the safety index, a driver's safety discomfort in a time step is simply measured by the degree to which he/she is faster than the preceding driver, divided by the safety distance between the two vehicles plus one. The constant technically prevents the denominator from being zero. We defined the traffic safety index at a particular time step then as one minus the maximum of safety discomfort among driver agents (equation 6). The higher the index, the safer is the traffic being perceived.

$$1 - max_{agents}\left[\frac{max(0, \Delta v)}{dist^p + 1}\right] \tag{6}$$

where $dist^p$ is again the preceding vehicle's distance to the vehicle in meters, and Δv the speed of the vehicle minus the speed of the preceding vehicle.

The comfortability in terms of abruptness of driving over time was measured by two global measures at the end of a run, i.e. by the average speed change between two subsequent time steps (average over vehicles and over the entire simulation period) (equation 7) and the average variation of speed change (equation 8).

$$mean_{agents}\left(mean_{s=0}^{S}(v^{(s)} - v^{(s+1)})\right) \tag{7}$$

where S is 10 000 - 1, and $v^{(s)}$ is the velocity at time step s.

$$mean_{agents}\left(std_{s=0}^{S}(v^{(s)} - v^{(s+1)})\right) \tag{8}$$

In addition to these indicators, we generate and analyze data on vehicle accelerations in order to get an impression in which dimensions the proposed ACC strategies tend to bring accelerations and whether these ranges are feasible.

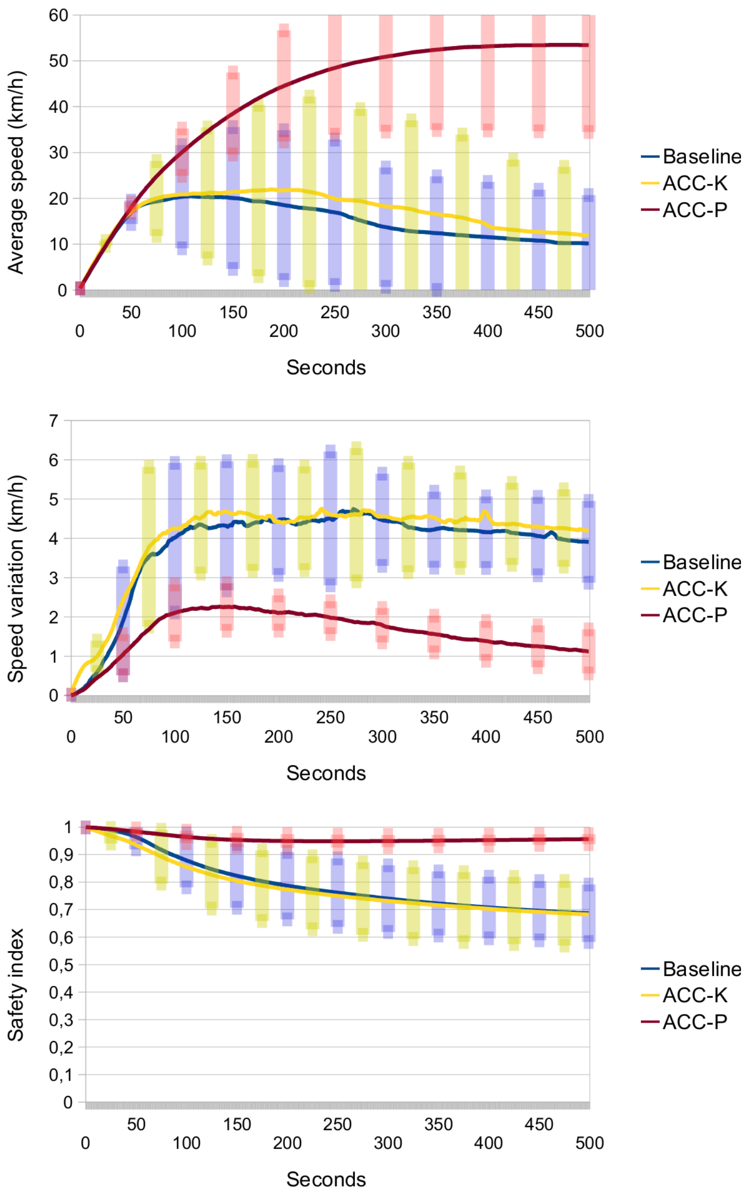

Figure 1: Results of first simulation set: Average speed, speed variation (standard deviation), and safety index simulated over time for the baseline, the strategy by Kesting et al. (2008) ACC-K, and the proposed strategy ACC-P.

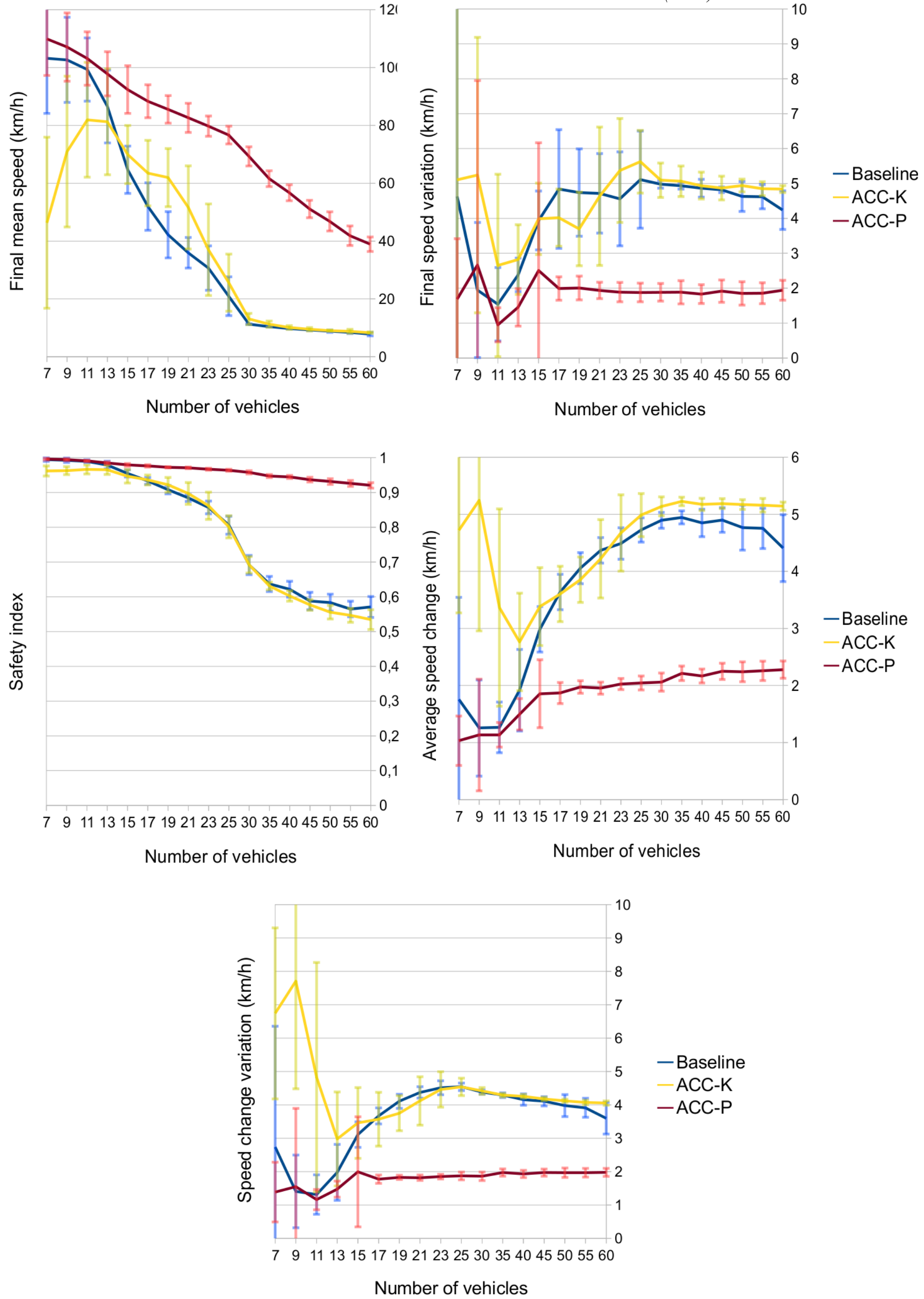

Figure 2: Results for first set of simulations: Final average speed, final speed variation, overall safety index, average speed change, and speed change variation for different vehicle densities (i.e. vehicle numbers). The baseline denotes simulations without an ACC strategy, ACC-K simulations with the strategy by Kesting et al. (2008), and ACC-P the proposed one.

3.3. Simulation results

The first set of simulations showed that stop-and-go traffic could be alleviated and the comfortability of driving could be increased by the proposed strategy, which we denote as ACC-P. In particular, the speed and safety index could be significantly increased over time with this strategy, and speed variation among vehicles could be significantly reduced over time (all with significance = 0.000) (Figure 1). All these and subsequent tests were conducted via Welch or T-tests, depending on whether variance was significantly different among datasets. In addition, the global indicators for abruptness of driving could also be significantly improved by the ACC-P strategy. In particular, average speed change and average variation of speed change of vehicles were 1.6 and 1.5 km/h per time step, respectively, as compared to 4.4 and 3.8 for the baseline, respectively. These differences were also both significant at a level of 0.000. In contrast, the strategy by Kesting et al. (2008), which we denote as ACC-K, could not significantly change average speed and the safety index over time, while variation of speed among vehicles was even slightly raised over time (significance = 0.003), indicating an increase of stop-and-go patterns. The global indicators for abruptness of driving were also significantly worsened. In particular, average speed change and average variation of speed change of vehicles were 4.7 and 3.9 km/h per time step, respectively, as compared to again 4.4 and 3.8 for the baseline, respectively.

Maximum accelerations over all scenarios and time steps were in the same range for the baseline (1.39 m/s^2), and the two ACC strategies (i.e. 1.51 m/s^2 for ACC-K and 1.39 m/s^2 for ACC-P). Maximum braking, on the other hand, was highest for the baseline, intermediate for ACC-P, and near zero for ACC-P. It can thus be concluded that both strategies operate within ranges of the baseline and are thus technically feasible for vehicles.

While for the first simulation set, the evolution of these indicators over time was of interest, for the second set we were rather interested into what final state the system converges, given different vehicle densities, and how these final states relate to vehicle density. Accordingly, we here only analysed the final values at the end of a run. In general, the second set of simulations confirmed the above findings more analytically. In particular, for vehicle densities (i.e. vehicle numbers) above 17, the use of ACC-P could significantly alleviate stop-and-go traffic and improve driving comfort (Figure 2). That is, final average speed and the safety index could be significantly raised, while final speed variation, average speed change and speed change variation were significantly lowered (all with significance = 0.000 for vehicle densities $\geq$ 17). Final average speed could be raised by up to 615 % from the baseline. For vehicles densities lower than 17, the indicators behaved similar to the baseline, indicating that the proposed strategy does not affect free-flow traffic. The findings for the strategy by Kesting et al. (2008), which we denote as ACC-K, were rather mixed. It seems that for low to intermediate vehicle densities, the use of ACC-K can slightly improve baseline traffic flow in terms of all indicators, while for low and for high vehicle densities the use of ACC-K even worsened traffic flow. These differences were significant at level 0.05 for very low (9), low to intermediate (19), and very high (60) vehicle densities (i.e. significance < 0.05). Remarkable is the negative effect of ACC-K in free flow. That is, under ACC-K, we have much lower final mean speeds and more abrupt speed changes for low vehicle numbers, as compared to the baseline (see Figure 2). This is explained by the ACC-K rule for the on-ramp zone. In particular, when entering a freeway zone next to an on-ramp, the ACC-K strategy envisages to set ACC parameters such that acceleration is increased and safe time gaps are reduced temporarily. When traffic is now in free flow at low vehicle densities, this abrupt temporary behaviour causes unintended turbulences that lead to traffic breakdown. Simulation tests showed that these turbulences only occur when this ACC-K on-ramp rule is active. All tests between the baseline and one of the alternatives were again conducted via Welch or T-tests.

4. Discussion

It could be shown that the proposed strategy is far more effective in terms of driving comfort and achieved speed than the one by Kesting et al. (2008). That is, stop-and-go traffic could be alleviated and transformed into more comfortable and much faster traffic flow, for a range of traffic situations. In contrast, the strategy by Kesting and colleagues ranged from slightly effective to adverse in these situations. Our findings challenge the idea that the thresholds, values and rules specified in the ACC strategy by Kesting et al. (2008) also disperse traffic congestion in other situations and settings. However, we must concede that these conclusions are so far only valid for our abstract freeway setting selected in this study, and that now more detailed tests via empirical records are required. Moreover, one of the concerns by Kesting and colleagues was that ACC parameters should only be slightly modified by the device, in order not to excessively harm the driver's feeling of authority over the system. This concern in particular influenced their ACC strategy design. We need to think about how to advance our proposed ACC strategy in case it violates such concerns and carry out corresponding assessments. For the moment at least, it can be stated that, purely technically, the proposed strategy outperforms its classification-based alternative. The final concern is that for this study we had to assume that all vehicles are equipped with and governed via ACC, which is currently not (yet) the case. Simulations for empirical settings that also account for human driving and allow potential human overriding of ACC strategies are therefore the next logical step. On the other hand, all these concerns may appear less important against scenarios of more futuristic scenarios of traffic, where drivers may have become used to assigning more of their authority to their devices, and more vehicles are generally equipped with intelligent technology. At least against this background, further testing of the proposed strategy seems worthwhile, given its frugality and technical effectiveness in organizing traffic in an emergent and distributed manner.

References

Baskar, L. D., De Schutter, B., Hellendoorn, J., & Papp, Z. (2011). Traffic control and intelligent vehicle highway systems: A survey. *IET Intelligent Transport Systems 5(1):*38-52.

Broucke, M. & Varaiya, P. (1997). The automated highway system: A transportation technology for the 21st century. *Control Engineering Practice, 5(11):*1583-1590.

Davis, L. C. (2004). Effect of adaptive cruise control systems on traffic flow. *Physical Review E 69, 066110* (2004).

Davis, L. C. (2012) Physica A 391 (2012). Mitigation of congestion at a traffic bottleneck with diversion and lane restrictions. *Physica A 391 (2012):* 679–1691.

Downs, A. (2004) *Still Stuck in Traffic: Coping with Peak-Hour Traffic Congestion.*The Brookings Institution, Washington D.C.

Kerner, B. S. (2004). *The Physics of Traffic*. Springer, Heidelberg.

Kesting, A., Treiber, M., Schönhof, M., & Helbing, D. (2008). Adaptive cruise control design for active congestion avoidance. *Transportation Research Part C 16:*668-683.

Kesting, A., Treiber, M. & Helbing, D. (2007). General lane-changing model MOBIL for car-following models. *Transport. Res. Rec. 1999:* 86-94.

Kesting, A., Treiber, M., Lämmer, S., Schönhof, M., & Helbing, D. (2006). Decentralized approaches to adaptive traffic control and an extended level of service concept. In: *Proceedings of the 17th International Conference on the Application of Computer Science and Mathematics in Architecture and Civil Engineering*. K. Gürlebeck and C. Könke (eds.). 12-14 July 2006, Weimar, Germany.

Lee H. K. & Kim., B. J. (2011). Dissolution of traffic jam via additional local interactions. *Physica A: Statistical Mechanics and its Applications 390(23-24)*: 4555-4561.

Li, K. & Ioannou, P. (2004). Modeling of traffic flow of automated vehicles. *IEEE Transactions on Intelligent Transportation Systems 5(2):*99-113.

Marsden, G., McDonald, M., & Brackstone, M. (2001). Towards an understanding of adaptive cruise control. *Transportation Research Part C 9:*33-51.

Treiber, M., Hennecke, A., & Helbing, D. (2000). Congested traffic states in empirical observations and microscopic simulations. *Physical Review E 62:*1805-1824.

Treiber, M. & Helbing, D. (2001). Microsimulations of freeway traffic including control measures. *Automatisierungstechnik 49 (2001):*478-484.

United States Department of Transportation. 2013. http://www.ops.fhwa.dot.gov/aboutus/opstory.htm.

Varaiya, P. (1993). Smart cars on smart roads: Problems of control. *IEEE Transactions on Automatic Control 38(2):*195-207.

Wilensky, U. (1999). *NetLogo version 4.0.4.* Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.