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Network-wide emission effects of cooperative adaptive cruise control with signal control at intersections

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Abstract

In the present paper, we report the findings from our initial analysis on the relationship of the penetration rate of vehicles with Cooperative Adaptive Cruise Control (CACC) and three flow performances regarding congestion and emissions in two test networks, which have different levels of complexity and different traffic control strategies. Our analysis shows that the possible effects of CACC on environment and traffic in near future is distinguishable. We further discuss the compatibility of existing urban traffic control management strategies with the CACC.

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Keywords: Cooperative Adaptive Cruise Control; SUMO; Emissions

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1. Introduction

In the 21st century, traffic congestion becomes inevitable for the most of the developed and crowded cities with the increase of the traffic demand and vehicle ownership. The reflection of the congestion on the human lives has several aspects, i.e. time loss, environmental problems, road accidents and consumption of the limited sources. By these reasons, communication technologies are adopted into vehicles for creating a network-wide control over the vehicles. Vehicle-to-X (V2X) and Cooperative Adaptive Cruise Control (CACC) concepts are utilized in many researches in order to find a solution for the aforementioned problems, however, these researches concentrate mostly on safety-related issues on highway traffic (Vahidi et al., 2018). For widening the concept of CACC, we handle the CACC as the possible solution on congestion related environmental problems in urban networks. In order to have such inferences, we use Eclipse Simulation of Urban Mobility (SUMO) as the microscopic traffic simulation

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software, and Omnet++ as the communication network simulation software (Krajzewicz et al., 2012). At the current stage of our work we report in the present paper, we assume that all the intersections existing on the networks we consider are signalized with different control strategies, i.e., fixed time and adaptive control. For fixed time signalization, the Webster method, which is a widely used calculation method for optimum cycle length since the 1960s (Webster, 1958), is applied. For adaptive signalization, we input the measurements from loop detectors implemented to the simulation model. Loop detectors are mostly used for traffic counts and occupancy measurements and for having adaptive signalization as well in many countries (Klein et al. 2006; Brilon and Wietholt, 2013). In our research, we alternate the penetration rate of CACC increasing 20% at each simulation in order to observe the gradual effects of CACC on urban network traffic flow. We also assume that with an increase in the rate of CACC, it is possible to obtain smaller headways in traffic (Jones, 2013). Thus, we consider a negative linear relationship between the penetration rate of vehicles with CACC and the headway. For preventing safety-related problems, we set up the model for the car-following parameters of SUMO (SUMO, 2019).

The rest of the paper is organized as follows: Section 2 presents a brief summary about the relevant literature corresponding to our study; in Section 3, the methodology and the simulation framework are described; Section 4 involves the information about our test cases; results from the simulations are given in Section 5; and Section 6 concludes the paper.

2. Literature Review

In the literature, CACC is handled as a multi-tasking control system over infrastructure, vehicles, and environment. In the present paper, we summarize a review on the studies on the effects of the CACC on traffic flow and on environment, and perform analyses with the motivation of contributing to the intersection of congestion and emission consequences.

In Delis et al. (2016), two distinct scenarios have been created in order to assess the impacts of CACC with varying penetration rates. While, it is expected that the existence of CACC equipped vehicles damp the traffic related disturbances, which are created externally, on a circular track in one of the scenarios, a roadway segment with a merging section is analyzed in the other scenario with the expectation that the disturbances, which are caused by merging vehicles, are damped quickly because of the CACC equipped vehicles. Authors' analysis, which is mostly on congestion related measures, has shown that with a penetration rate of 30% it is possible to have an observable improvement on density, however for damping all disturbances, a 100% penetration rate of CACC equipped vehicles is needed. In Askari et al. (2017), an analysis is conducted in order to observe at signal controlled intersections the effects of changing rates of penetration. Authors modify the Intelligent Driver Model (IDM) for CACC in terms of observing the effects of a number of car-following model parameters including the reaction time, the headway, and etc. Results from Askari et al. (2017) show that at each penetration rate, there has been an improvement in traffic conditions. As in conjunction with the existing literature, we aim to observe the effects of varying penetration rates in the present paper.

The existing literature about environmental effects of CACC is mostly on energy efficient driving maneuvers and eco-routing optimization for a network. In our study, differently from the literature, emitted pollutants from the given routes are the base point of our analysis. In Wang et al. (2017), platooning maneuvers are studied in more details. Varying behavior for platoon formation, gap regulating, splitting, and merging maneuvers have been analyzed in Wang et al. (2017). However, since the simulations are conducted for considerably small scales, the effectiveness of the algorithm used is open to discussion that requires its performance evaluation in larger scenarios. Also, the simulations are constrained in terms of driving behavior. For a clear judgement for the algorithms, different scenarios with increased randomness are better to be simulated. In Vahidi and Sciarretta (2018), several studies are reviewed in order to underline the potential of CACC on energy efficiency under different conditions including lateral motion parameters, types of traffic and intersection control, and road topology as well as the traffic conditions. The comparison of studies are divided into two, in the first part the obtained results from the studies are discussed and in the second part, with the obtained results, the types of developments that can be provided in terms of energy efficiency are discussed. Homchaudhuri et al. (2017) have proposed an algorithm that makes use of the location information of vehicles retrieved via V2X communication. The main objective in Homchaudhuri et al. (2017) is reducing the total duration of idling vehicles, which enables to decrease emissions. The algorithm proceeds dependent on the decision of a single vehicle's traversing the or decelerating at an intersection in order to reduce or eliminate idling duration that is why the signal phases and timing information have to be shared with the vehicles by the infrastructure. Several safety constraints are defined for the algorithm in order to provide safer deceleration behavior. According to the simulation results in Homchaudhuri et al. (2017), it is possible to obtain 50% fuel economy with the employment of the algorithm.

As documented in the literature, at each penetration rate different levels of improvements can be obtained, however, improvements in most of the cases are valid only for the modeled networks and scenarios. Also, it is possible to obtain reduction in emissions at each penetration rate. In the present study, our main goal is to find an optimum penetration rate and discuss the compatibility of CACC with different traffic control strategies. Our main contribution is two-fold: to create a discussion about the transition process into the autonomous traffic environment; and, to point out the possible gradual effects of the CACC for the urban networks in the near future in the aspects of traffic and environment.

3. Literature Review

As aforementioned, open source microscopic traffic simulation software Eclipse SUMO is utilized in order to generate and analyze traffic characteristics (Behrisch et al., 2011; Akyol et al., 2019). SUMO enables us to define different vehicle types and define traffic flows and routes, these can be achieved via another code editor software. Also with NETEDIT, which is an internal tool of SUMO, it is possible to create traffic network easily. Intersection control strategies are also defined in NETEDIT. Given the varying and detailed features of the Eclipse SUMO in dealing with modeling and control of road traffic, in addition to our previous experience on the relatively extensive computing load of some commercial software for modeling similar schemes (e.g. Abuamer et al., 2016; Abuamer et al., 2017; Sadat and Celikoglu, 2017), we have preferred the Eclipse SUMO in our present work.

For adaptive signalization, loop detectors should be implemented. The locations and types of loop detectors are defined via code editor software and the codes are added into configuration file of SUMO. For simulations, SUMO reads only a configuration file, thus all the other defined files must be added into configuration file. For fixed time signalization, we use Webster method and the calculated cycle lengths and splits are written into the network file via NETEDIT. In order to provide Vehicle-to-Vehicle (V2V) communication, we use Omnet++ and Veins. Veins framework enables us to create vehicle like nodes in Omnet++ and provides a connection between SUMO and Omnet++. Traffic Control Interface (TRACI) tool of SUMO connects to Veins and provides information flow between SUMO and Veins.

3.1. Car-following model

The default car-following model of SUMO is Krauss car-following model, which is a "safe speed" based model (Krajzewicz et al., 2005). The function of the safe speed at the next time step uses the speed of the leading vehicle, speed of the following vehicle, the headway between these vehicles and defined human reaction time as input parameters. This equation stands for the safety of the drivers however, this safe speed term can be inappropriate for traffic flow or vehicles in terms of the motor capacities of the vehicles and the traffic legislation. Thus, a "desired speed" term is defined, which is the minimum value of accelerated speed, safe speed, and speed limit. For having a more realistic traffic flow, the acceleration and deceleration behavior of the vehicles are changed with random parameters, then applied on the desired speed for the calculation of the speed at the next time step.

3.2. Emission model

Handbook Emission Factors for Road Transport (HBEFA) model, which is based on power demand calculation of Passenger Car and Heavy Duty Emission Model (PHEM), is adopted for having an emission based analysis. PHEM has the ability of calculating the power demand for various speed profiles and road topologies. This calculation is based on vehicle dynamics and the actual engine speed for any vehicle combination. The fuel consumption and emissions are then interpolated from engine maps. HBEFA emission factors are found in the connection between the calculated engine power demand, engine speed and measured emission from real world measurements (Hausberger et al., 2009).

3.3. Test cases

In order to analyze the impacts of the CACC on flow performances at network scale with signal control at intersections, we design the present study using two hypothetical networks as shown in Fig. 1, i.e., T1 and T2, which have same number of intersections with different number of intersection legs. It is assumed that the test networks are urban networks, because of that, the speed limit is defined as 50 km/h (a priori information). The networks selected, whose performances under intersections with no control assumption have been previously figure out in Erdagi et al. (2019), are simulated with 0% to 100% penetration rate of vehicles with CACC. At each simulation, the penetration rate is increased by 20%. We assume that: vehicles communicate with each other in a 100 meters range; none of the networks has a Road Side Unit (RSU), thus the control is provided in a decentralized V2V environment; and, there are no obstacles in the networks, such as buildings, and etc., that can attenuate the wireless communication. For observing the effects of randomness, each simulation has repeated 10 times and totally 240 simulation are conducted.

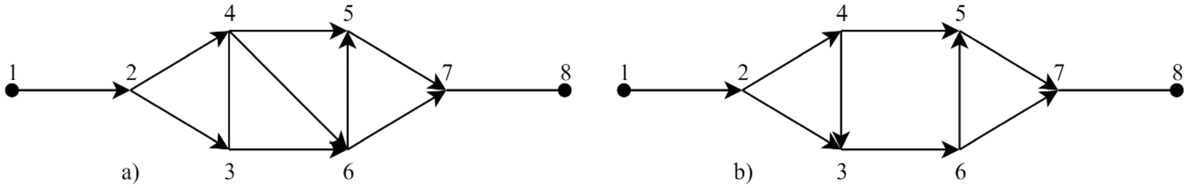

Fig. 1. a) T1 Network; b) T2 Network.

T1 and T2 networks have 6 intersections. In T1 and T2 networks, intersections with solely diverging maneuvers are not signalized. Each of the links in networks have a length of 1 km and all the links of T1 and T2 are one-way roads. From Fig. 2, it can be seen that the demand profiles to load the networks are time-varying with varying maximum traffic volumes. The origins of the networks vary. For T1 and T2, the vehicle loading node is “1” and the destination node is “8”, however for T1 five routes are defined and for T2 four routes are defined.

In order to differentiate vehicles with CACC from human driven vehicles we define two types of vehicles. Type-I represents the vehicles with CACC, and Type-II represents the human driven vehicles. Both types have identical features, i.e., vehicle mass equals 1200 kg, frontal areas are 2.5 m2, drag coefficient is 0.32, air density is 1184 kN/m2, and rolling resistance is 0.0015. Vehicles have gasoline engines in accordance to Euro Norm 6; as well, the maximum acceleration and deceleration of vehicles are assumed to be 4.5 m/s2. In order to observe the effects of different control strategies, we design two scenarios.

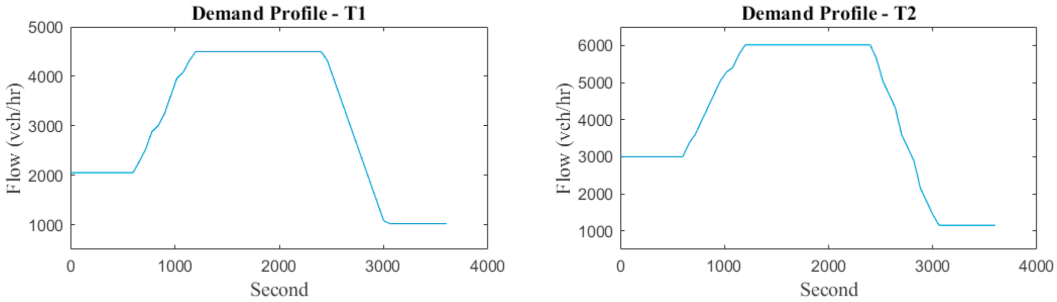

Fig. 2. Demand Profiles of T1 and T2 Networks, respectively.

In Scenario-1, the intersections, which are designed to be signalized, are fixed time signalized. The cycle lengths and splits are calculated by the Webster Method according to predefined traffic flows. In Scenario-2, the intersections, which are designed to be signalized as well, are adaptively signalized. We base the adaptive signalization rule on the time difference between the successive vehicles approaching on critical movements. If the headways in the critical movement are less than 3 seconds, then the green phase can be extended until the maximum duration limit. This limit is set as the two times of the given green phase so that the cycle lengths change in order to adapt themselves according to changing traffic conditions. The initial phases for adaptive signalization are defined after simulation trials in order to find the optimum scheme that provides the minimum stop-and-go movements. For both of the scenarios, it is assumed that it is safe to allow shorter headways as the penetration rate of the CACC is increased. Thus, we have defined a negative linear relation between the headway and the penetration rate. The minimum allowed headway is 1.5 sec for 0% penetration and decreases 0.18 sec for each 20% increase of penetration rate. As a result, for a 100% penetration rate of CACC the minimum allowed headway becomes 0.6 sec (Nowakowski et al., 2011).

4. Results

As we seek an optimum penetration rate for CACC equipped vehicles in terms of traffic and environmental problems in urban networks we consider the Total Time Spent (TTS) and the Number of Stop-and-Go (NSG) movements as the comparison parameters on traffic-related problems. In Fig. 3 and Fig. 4, it is shown that with the increase of the penetration rate significant improvements are achievable in NSG and TTS values for Scenario-1 and Scenario-2. However, until 60% penetration rate of CACC equipped vehicles the TTS values are increased for the

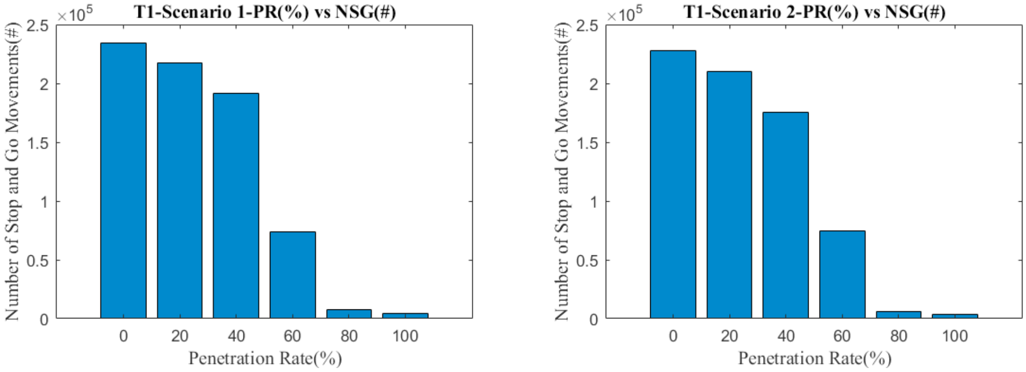

Fig. 3. Penetration Rate and NSG relation for T1 Network in Scenario-1 and Scenario-2, respectively.

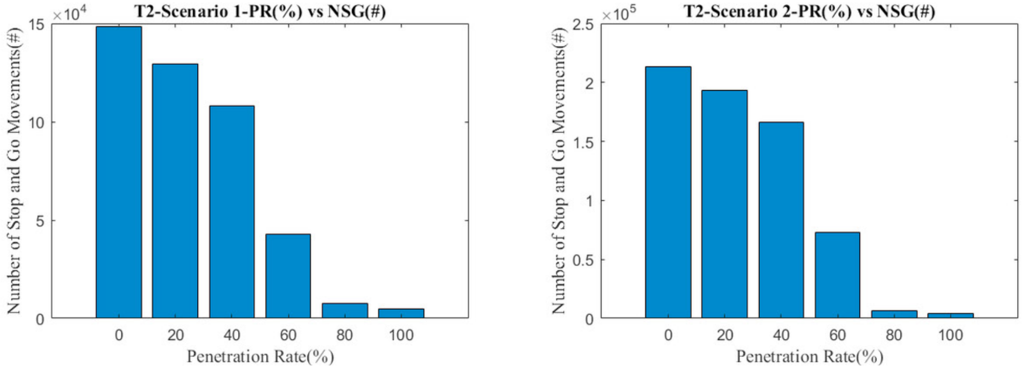

Fig. 4. Penetration Rate and NSG relation for T2 Network in Scenario-1 and Scenario-2, respectively.

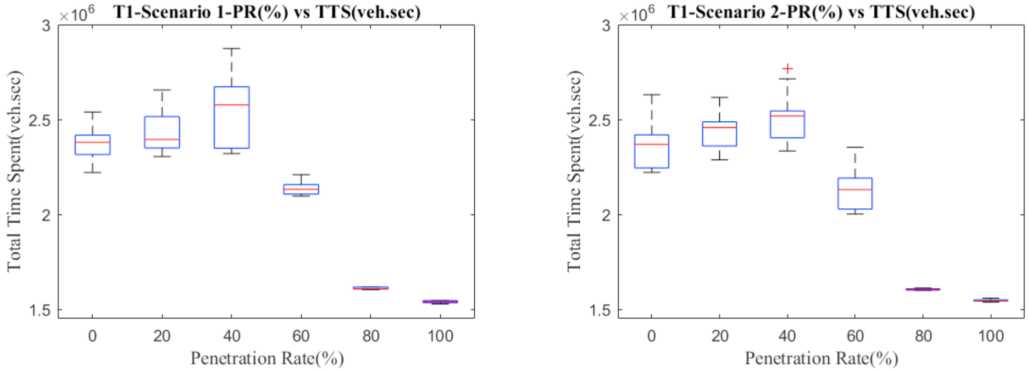

Fig. 5. Variation of TTS values with respect to Penetration Rate for T1 Network in Scenario-1 and Scenario-2, respectively.

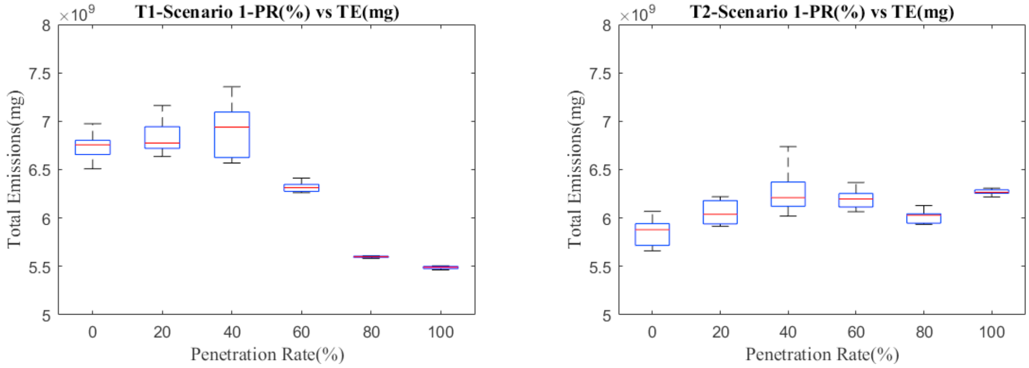

Fig. 6. Variation of TTS values with respect to Penetration Rate for T2 Network in Scenario-1 and Scenario-2, respectively.

test cases. The variation of the NSG and TTS values are reduced as shown in Fig. 5 and Fig. 6. The harmonization effect of CACC is observable even with a 20% penetration rate however, with an 80% penetration rate, the improvements are highly significant. The results satisfy the expectancy of ours, which is providing a harmonized and cooperative traffic flow. On a real network with a calibrated human imperfection parameter of the adopted car-following model can result in different results, however in a general aspect, the improvement trend of traffic flow would be similar to our cases, which will further be investigated in details in our future research. For Scenario-1 and Scenario-2, the most effective penetration rate is 100% for traffic-related optimization.

However, the adaptive control strategy of ours is more adequate for cooperative traffic flow with smaller headways, since several different adaptive control strategies should be tested, and with the Vehicle-to-Infrastructure communication, a network-wide optimum control strategy could be provided in a more effective fashion.

For observing the environmental effects of the CACC, the Total Emission (TE) values are taken into consideration. The TE values presented are the sums of emitted CO, CO2, NOx, HC, and PMx and given in milligrams. The results presented in Fig. 7 show that the increase of the penetration rate has diverse effects on TE values. The complexity of the test network and the control strategy are effective on the TE values, as well. Thus, a discussion on the variation of TE is more accurate. As shown in Fig.8, the increase of the penetration rate of CACC keeps the TE values in a narrower range and reduces the variation of TE values. Therefore, it is seen that the disturbances, which are caused by human nature, are damped by the CACC equipped vehicles.

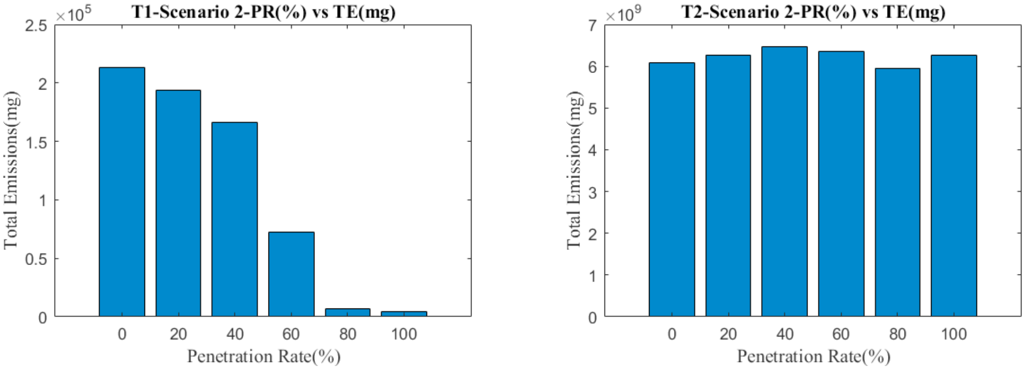

Fig. 7. Penetration Rate and TE relation in Scenario-2 for T1 and T2 Networks, respectively.

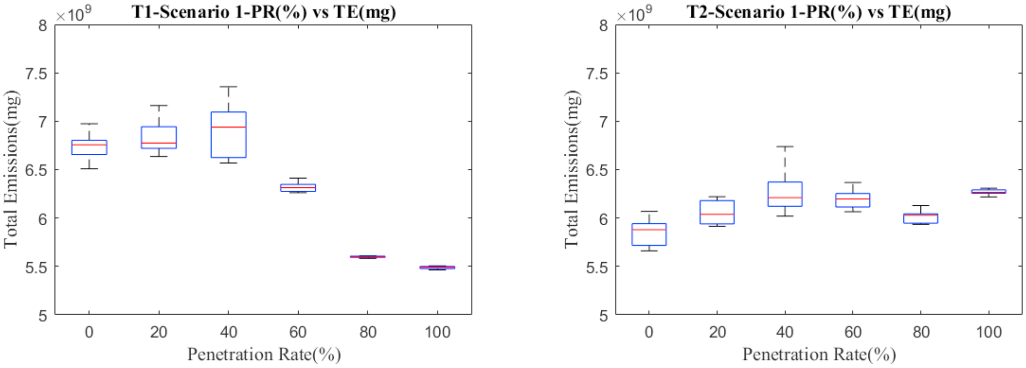

Fig. 8. Variation of TE values with respect to Penetration Rate in Scenario-1 for T1 and T2 Networks, respectively.

5. Conclusion and Future Research

An analysis, for seeking an optimum penetration rate of CACC equipped vehicles in urban networks, is conducted based on the simulation results from two hypothetical networks. Two different scenarios are designed for observing the effect of CACC with different strategies applied to control intersections. In Scenario-1, networks have fixed time signalization according to Webster Method and in Scenario-2, adaptive signalization is applied to control intersections. Both of the scenarios are simulated with varying penetration rates from 0% to 100%. At each penetration rate increase, the minimum allowed headway is decreased linearly from 1.5 sec. to 0.6 sec. in accordance with the study of Nowakowski et al. (2011). Each simulation case is conducted 10 times and the harmonizing effect of CACC on traffic flow is observed. The analysis is divided into two parts in order to differentiate the effects of CACC on traffic operations and environmental problems. The increase of the penetration rate of CACC equipped vehicles has a significant improving effect on TTS values after it is reached 60%, however, even with a 20% penetration rate a reduction in NSG values is achieved. The second stage of the analysis is based on the effects of CACC on the environment, therefore, the total of emitted pollutants are taken into consideration. Based on the TE values, a clear conclusion on optimum penetration rate cannot be reached due to differences in network characteristics. Therefore, each of the networks should be handled in more details in order to clarify the importance of network characteristics, including the link length variation, dilemma zone lengths, lane disciplines, and etc. We have observed in the present study the positive impact of the increase in the penetration rate has been observed at simulations conducted at network scale.

As the directions of our future research, we will handle more realistic networks with shorter links and different link characteristics, and real-world networks with existing control strategies. A thorough sensitivity analysis using appropriate methods will be conducted in order to clarify the effectiveness of each of the parameters of the different car-following models adopted and the communication framework on the cooperative traffic environment.

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