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Emission Effects of Cooperative Adaptive Cruise Control: A Simulation Case Using SUMO

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Abstract

The recent advances in adaptive control and autonomous vehicles have given rise to the studies on cooperative control of road vehicles, and the consequent effects on traffic flow performances. In this paper, we summarize our findings from a simulation-based solution of a problem that seeks the joint optimization of a number of link-based performances of vehicular traffic flow considering explicitly the emissions exhausted using the Eclipse SUMO micro-simulation environment in order to discuss the effectiveness of the penetration rates of cooperatively controlled vehicles in mixed traffic.

1 Introduction

The recent advances in adaptive control and autonomous vehicles have given rise to the studies on cooperative control of road vehicles, and the consequent effects on traffic flow performances. In order to find an optimum penetration rate of vehicles with Cooperative Adaptive Cruise Control (CACC) for varying scenarios of mobility demand and road geometry, we have explicitly considered two measures as the total time spent and the total emissions are documented in the literature to be correlated with each other [1]. We have selected the total time spent and total emissions on purpose to have an insight about the effectiveness of the CACC aiming to obtain a steady state of traffic flow. We have tested two hypothetical road networks with different levels of complexity, in which all the nodes are assumed to behave as a signalized intersection. For simulation-based analyses, we have made use of the open source microscopic simulation software Eclipse Simulation of Urban MObility (SUMO) [2]. We have assumed in our analyses that at the intersections: in a range of 100 meters all the vehicles are in Vehicle to Vehicle (V2V) communication, as in [3]; and the minimum headway between cooperatively controlled vehicles equals 2 seconds. For the implementation of our assumptions, CACC vehicles are integrated in Eclipse SUMO via Omnet++ and Veins, and the needed arrangements are designed in Eclipse

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SUMO. The setup of the simulation model required a number of assumptions as well. All the vehicles are assumed to have the identical emission model. Parameters including the vehicle mass, drag coefficient, air density, frontal area, and rolling resistance are used as same as in the relevant literature [4]. Vehicles are routed from a specified fixed origin node to a destination node. In order to clearly observe the effectiveness of the CACC with varying penetration rates of cooperatively controlled vehicles, each of the networks is simulated with changing rates of vehicles with CACC from 0% to 100%. The researches in recent years document that mostly the effects of CACC on safety is studied [5]. We therefore contribute to the literature with this initial study by analyzing the link and network-wide flow performances with respect to the effects of CACC, specifically the exhaust emissions.

The paper is organized as follows: Section 2 presents the relevant literature corresponding to our study; Section 3 introduces the methodology and the simulation framework; Section 4 involves the information about the simulation trials; results from the simulations are evaluated in Section 5; and Section 6 concludes the paper.

2 Literature Review

In the literature, studies on CACC is divided into categories, i.e. effects on traffic, effects on safety, effects on environment and in this paper, the studies on the effects on traffic and the effects on environment are handled. In [6], two different scenarios have been generated for observing the effects of penetration rates of vehicles with CACC. In the first scenario, there is a circular track and it is expected that, the vehicles with CACC should damp the disturbances, which are generated by the authors externally. In their second scenario, a network element with a merging section is observed. The disturbances, which are created by the merging vehicles, are expected to be damped. In [7], the term of platoon is implemented on the vehicles with CACC. They conduct a 3 hours of simulation with three different scenarios. In the first scenario, there is fixed-time signalized intersection, and in the other scenarios, the control is maintained with an adaptive signalized control scheme. The difference is their freedom on changing the phases in a minute. In the second and third scenarios, there is also V2I (Vehicle-to-Infrastructure) communication. They made their comparison on the changes on the length of queues and the total delay. In [8], a new control strategy is proposed based on game theory. At an uncontrolled 4-legged intersection, vehicles with CACC communicate with each other and make a move about their speed profile, i.e. deceleration, and acceleration. Their assumption is that, all the vehicles have CACC and there is no communication delay. Their results show that, in their scenario it is possible to obtain 49% of reduction in travel time delay average and 89% of reduction in delay when it is compared to a scenario with all way stop sign controlled intersection. In [9], a Cooperative Merging Assistant (CooPMA) is introduced. With the V2V and V2I communication, they tried to distribute the spacing between vehicles via using a cooperatively controlled vehicle. It can be seen from their results that, it is beneficial to create a denser traffic states for having a large single spacing between platoons. In [10], the effects of penetration rates of vehicles with CACC or ACC are investigated at signalized intersections. They change the Intelligent Driver Model (IDM) for CACC in terms of observing the effects of reducing headways, distance to the leading vehicle and reaction time. Based on their 1-hour simulation results, at every penetration rate CACC has improved the traffic conditions. As in conjunction with the existing literature, we aim to observe the effects of varying penetration rates. However in the literature studies are mostly on urban scenarios and V2I communication. There are limited works on CACC with higher speeds.

The environmental effects of road traffic is of great importance in our analysis, however, existing studies are mostly about eco-routing for CACC and energy efficient driving for CACC. Emissions are handled mostly in part using results. In [11], the effects of re-routing on emissions based on weather conditions are investigated. In this study, it is highlighted that, with an advisory re-routing option, it is possible to reduce emissions, however, the compliance rate of drivers is the main determinant factor. In [12], a highway segment from Sri Lanka is examined. They created a scenario with 5000 vehicles and a randomly placed platoon with eight vehicles. They used SUMO, Veins and Omnet ++, however they have no numerical results about emissions and they supposed that, having a traffic flow with better conditions results a decrease in emissions. In [13], platooning maneuvers are studied in more details. They proposed different behavior for platoon formation, gap regulating, splitting and merging maneuvers. However, they conduct their simulations in a very small scale and the improvements are relatively small than expected. In [14], they proposed a Model Predictive Control (MPC) scheme for vehicle dynamics and lane change maneuvers. They used their control scheme for a highway segment with an on-ramp and an off-ramp segment in a simulation model in SUMO. They explained the emission model in SUMO and explained the effects of parameters on power-demand of a vehicle in the simulation. In [15], many studies are compared and the potential of energy efficiency of CACC is discussed in terms of different traffic conditions, lane change maneuvers, intersection control types and road topology. In [16], an energy efficient algorithm is proposed, which uses location information of vehicle from V2I and V2V communication. The objective was decreasing the number of stopped vehicles at signalized intersections, by that it is possible to decrease emissions from idling vehicles. For achieving the objective, vehicles are assumed to use signal phases and timing information from signals and decelerate to an optimum velocity. In [17], they proposed varying speed profiles for vehicles according to changing spacing. The objective was to prevent the stopping of vehicles in the use of V2I and V2V communication. However, it is stated that, there is a trade-off between emissions and travel delays. In [18], string stability is discussed in terms of platooning. They stated that, with platooning vehicles with CACC, it is possible to reduce air drag resistance and have reduction in emissions.

Considering the findings from the existing relevant literature , it can be seen that different levels of development can be obtained for different penetration rates of vehicles with CACC. However, it is possible to have reduction in emission for each penetration rate. In our study, the main goal is to find an optimum penetration rate and discuss the effects of CACC in the near future. Our main contribution in the summarized piece of our research is that we use current developments to create an area for observing possible gradual developments in the future in terms of traffic conditions and environment for urban networks.

3 Methodology

As aforementioned, we have used Eclipse SUMO as microsimulation software. Eclipse SUMO is an open source microsimulation software, which is developed by DLR. SUMO contains several tools for different tasks and in our study we use NETEDIT and TraCI. In [19], it is explained that, parameters for creating networks are simple in SUMO. In our study we have used codes for creating a node file and an edge file and combined them for creating a network via NETCONVERT, which is an another tool of Eclipse SUMO. We also assumed that the vehicles decide their routes. In our study, we have used Veins and Omnet ++ for modelling CACC and VANET. The interaction between Eclipse SUMO and Veins is ensured via TraCI. TraCI is the traffic control interface of Eclipse SUMO and operated in Python language. The interaction between Eclipse SUMO and Veins is shown in Fig-1.

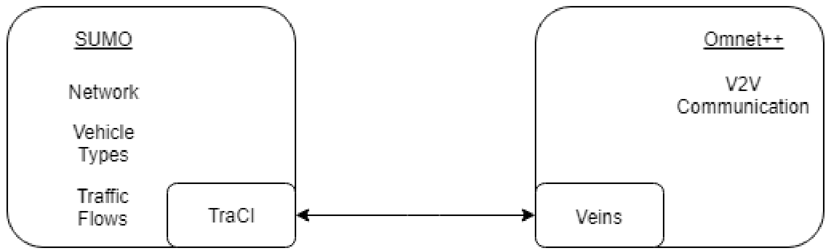

Figure 1: The Interaction between SUMO and Omnet++

3.1 Car Following Model and Simulation Setup

Default car following model of Eclipse SUMO is a modified version of Krauss car following model [20]. Original Krauss car following model is developed by Stefan Krauss in year 1997. This model is based on "safe speed" term. The safe speed is computed as follows:

$$v_{safe} = v_l(t) + \frac{g_n(t) - v_l(t)T}{\frac{v_f(t)+v_l(t)}{2b} + T} \quad (1)$$

where $v_l(t), g_n(t), v_f(t), b$ and T represent respectively the speed of the leading vehicle at time t, spacing between leading vehicle and following vehicle at time t, speed of the following vehicle at time t, maximum deceleration and reaction time of the drivers. By Eq-1 the safety is ensured for the vehicles. However, the safe speed can exceed the speed limit or it can be beyond the speed that a vehicle can reach. Because of that, the desired speed term is created and can be calculated as follows:

$$v_{desired} = Min(v_f(t) + at, v_{safe}, v_{limit}) \quad (2)$$

where a, t and v_{limit} represent respectively acceleration, time and the speed limit. Desired speed is the minimum value of these three constraints. By Eq-2, safety related, law related and vehicle related constraints are satisfied. In Eclipse SUMO, for modelling more human-like driver, an imperfection parameter is added, nevertheless, this parameter is randomly chosen at each time step for each vehicle, by that a randomness in spacing can be achieved. Thus the speed of following vehicle becomes,

$$v^f_{t+\Delta t} = Max(0, v_{desired} - \in a\eta) \quad (3)$$

In Eq-3, $\in$ and η represent respectively noise amplitude and a random number. By this equation, vehicles with different speeds can be obtained.

3.2 Emission Model and Simulation Setup

As to figure out emissions, we use the HBEFA3 based emission model of Eclipse SUMO. In Eclipse SUMO, the power demand of the vehicle is calculated as follows,

$$P = c_0 + c_1 va + c_2 va^2 + c_3 v + c_4 v^2 + c_5 v^3 \quad (4)$$

In the Eq-4, coefficients of c_n are dependent on vehicle type and engine type of the vehicles and from HBEFA database the emission factors are chosen for the calculated power demand.

4 Simulation Trials

In our study, we have considered two hypothetical networks, i.e. T1 and T2. The networks are given in Fig-2 and Fig-3 respectively.

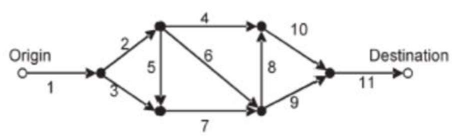

Figure 2: T1 Network

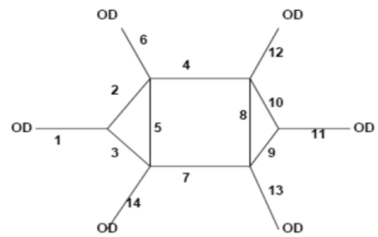

Figure 3: T2 Network

The networks considered have identical numbers of intersections, but different numbers of intersection legs. Each link in networks has a length of 1 km. All the links existing on the networks assumed as urban roads, thus we have defined a speed limit of 50 km/h. In scenario one, the intersections are fixed time signalized and in the scenario two intersections have an adaptive signalization. Only the intersections with a merging or crossing conflict are controlled with signalization in each scenario. It is assumed that there are no objects or buildings in the networks that can attenuate the V2V communication.

All the simulations has a duration of 3600 seconds and as aforementioned, each network is simulated with varying penetration rates of vehicles with CACC. The penetration rates of vehicles with CACC started from 0% and at each simulation, the penetration rate is increased by 25%. We created two types of vehicles, i.e. Type-I and Type II. Both the types have identical features, i.e., vehicle mass equals 1200 kg, frontal areas are 2.5 m^2, drag coefficient is 0.32, air density is 1184 kN/m^2 and rolling resistance is 0.0015. Vehicles have gasoline engines in accordance to Euro norm 6; as well, the maximum acceleration and deceleration of the vehicles are 4.5 m/s^2. Only difference is that Type-I represents the vehicles with human drivers and Type-II represents the vehicles that are cooperatively controlled vehicles. For observing more realistic traffic conditions, we implemented demand profiles, which vary with time. Vehicle loading is implemented using the origin nodes for T1 network and vehicles are routed from origin to destination. The vehicles decide the intermediate nodes. The time-varying demand profiles of T1 and T2 are given in Fig-4. In T2 network, all the links are divided roads, vehicles are loaded at all OD points, and the five identical demand profiles are implemented for each OD point. As in the T1, vehicles decide the intermediate nodes in T2 also.

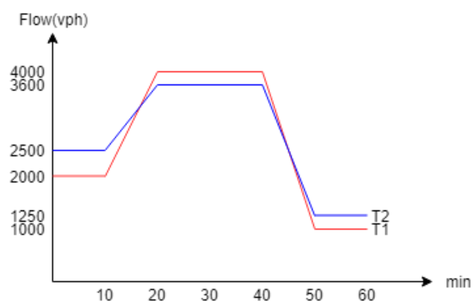

Figure 4: Demand Profiles

In Scenario-1, the controlled intersections are fixed time signalized. For T1, cycle lengths are chosen as 90 seconds and each green phase has a duration of 42 seconds. For T2, cycle lengths are chosen as 120 seconds. At the three-legged intersections each green phase has a duration of 58 seconds and at the four-legged intersections the duration of green phases varies, i.e., the green phases of the connections, which are from the center of the network, have a duration of 10 seconds and the other green phases are 52 seconds. In the Scenario-2, the controlled intersections are adaptive signalized. For this purpose, loop detectors are installed 5 meters away from the intersections. For T1, the links in the east-west direction are assumed to have priority over the links in other directions and for T2, the connection with shorter green phase duration is assumed to have a lower priority than the others. In Scenario-2, we let the higher priority links extend their phases until the phase durations are doubled or the headways between the vehicles, that are on the high priority links, are more than 20 seconds. The other phase durations are assumed to be constant.

For modeling vehicles with CACC, it is assumed that vehicles in a range of 100 m radius are in V2V communication. As aforementioned, there are no obstacles in networks, which can prevent the communication. The minimum headway between cooperatively controlled vehicles is defined as 2 seconds.

5 Results and Discussion

We have tried to find an optimum penetration rate of cooperatively controlled vehicles in terms of having improvements on traffic and environmental related problems. For analyzing traffic improvements, we have selected the Total Time Spent (TTS) as the comparison parameter. We plot the graphs of Total Time Spent values versus penetration rates of cooperatively controlled vehicles for each network. For the Scenario-1, the Total Time Spent versus Penetration Rate (PR) graphs are given in Fig-5 and Fig-6 for T1 and T2 respectively.

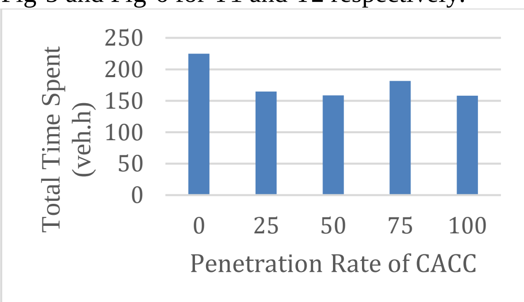

Figure 5: TTS-PR of T1 Network

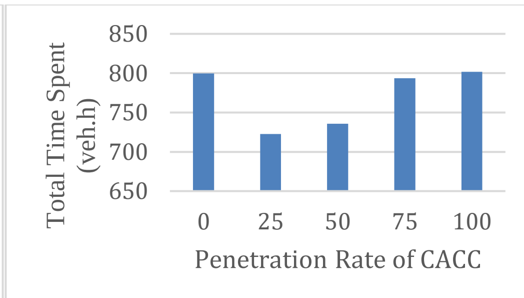

Figure 6: TTS-PR of T2 Network

Additionally, we have chosen Total Emission (TE) values for the cases of environmental comparison. Three pollutants are chosen for total emission value, i.e., HC, NOx and PMx. We plot the total emission versus penetration rates of CACC. The graphs for T1 and T2 are given in Fig-7 and Fig-8 respectively.

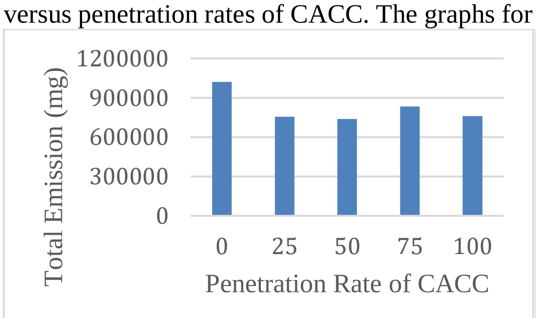

Figure 7: TE-PR of T1 Network

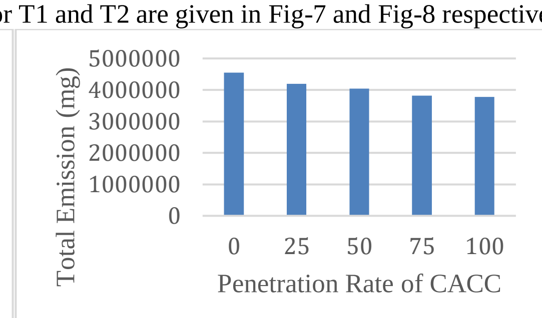

Figure 8: TE-PR of T2 Network

In Scenario 1, for T1, at all penetration rates, improvement in TTS and improvement in TE are achieved. However, for T2, increase of penetration rate has a negative effect on traffic, although emissions are reduced. Thus, we can observe the tradeoff between TTS and TE and from the results of these two networks, optimum penetration rate for this test case is between 25% and 50%. For the Scenario-2, the same graphs are plotted. The graphs are given from Fig-9 to Fig-13.

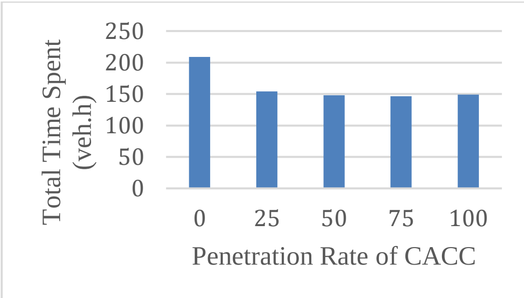

Figure 9: TE-PR of T1 Network

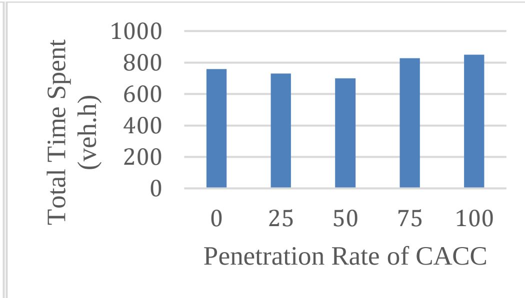

Figure 10: TTS-PR of T2 Network

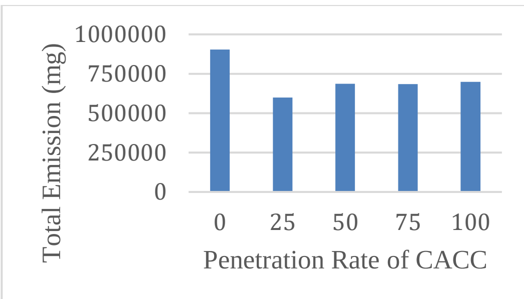

Figure 11: TE-PR of T1 Network

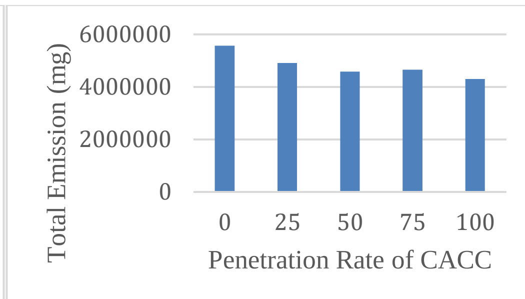

Figure 12: TE-PR of T2 Network

In Scenario-2, similar patterns in results are observed with Scenario-1. However, the negative impact of increase of CACC on traffic reached 12% with a penetration rate of 100%. For T1, at all penetration rates, significant improvements are achieved, however there are some fluctuations in TTS values, both of the scenarios are considered, it can be said that for the test networks considered, the optimum penetration rate of CACC is between 25% and 50%. For Scenario-1 and Scenario-2, the improvements (%) are given in Table-1.

	Scenario-1			
	T1		T2	
Penetration Rate	Improvement in TTS (%)	Improvement in TE (%)	Improvement in TTS (%)	Improvement in TE (%)
25	26.74	25.92	9.64	7.85
50	29.43	27.59	8.03	11.05
75	19.12	18.32	0.76	15.99
100	29.73	25.41	-0.23	16.95
	Scenario-2			
	T1		T2	
Penetration Rate	Improvement in TTS (%)	Improvement in TE (%)	Improvement in TTS (%)	Improvement in TE (%)
25	26.25	33.67	3.68	11.78
50	29.22	23.99	7.90	17.68
75	29.89	24.17	-8.98	16.54
100	28.68	22.79	-12.06	22.84

Table- 1: Resulting Improvements

6 Conclusions and Future Research

In this study, in order to find an optimum penetration rate of CACC in urban road, we have created two hypothetical test networks with different levels of complexity and conducted simulations on microscopic simulation software Eclipse SUMO. Two different scenarios are created for observing the effect of CACC with different control measures on the intersections. In Scenario-1, networks have fixed time signalized intersections and in Scenario-2, adaptive signalization is applied to the intersections. Both of the scenarios are simulated with varying penetration rates from 0% to 100%. As a result, the increase in the penetration rate of CACC has a positive impact on environment, and at least 20% reduction in total emissions are achievable for most of the cases. However, the increase in the penetration rate of CACC can increase the total time spent. In the near future, the positive impact of CACC on environment will increase, however, for traffic conditions the results tell us that the existing traffic control strategies have to be upgraded in accordance with the increases on the penetration rate of CACC.

Our future research focuses on observing the effects of CACC on environment and traffic in real urban networks in order to find a valid scale for applying traffic control strategies and upgrade them for having a more compatible traffic for vehicles with CACC.

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