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Effects of Bus Platooning in an Urban Environment

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Abstract— **One typical application of intelligent transportation systems (ITS) is vehicle platooning where a group of vehicles travel with smaller inter-vehicle distance safely, improving energy efficiency as well as road capacity and traffic safety. Truck platooning on highways has been widely studied and showed the aforementioned effects. However, the platooning of buses in urban environments have not been investigated thoroughly in the literature. This paper examines the effects of bus platooning with respect to traffic control and energy consumption.**

Microscopic traffic simulations have been conducted to demonstrate that bus platooning improves the quality of service of buses and maintains the quality of the traffic flow. Subsequently, driving cycles of buses generated from the simulation study serve as input for an energy consumption analysis, showing that not only bus platooning itself result in a reduction of energy consumption but the traffic signal prioritisation for bus platooning lead to additional energy savings.

I. Introduction

Vehicle platooning is one typical application of intelligent transportation systems (ITS), it refers to an operational practice in which multiple vehicles follow one another closely. The intra-platoon distance is maintained shorter compared to today's practice, which leads to reduced aerodynamic drag, particularly for the vehicles in the middle of a platoon. The change in the aerodynamic drag results in reductions of energy usage, traffic congestion, and hence emissions [1–5].

A. Vehicle Platooning

Modern driver assistant systems and vehicle-to-vehicle (V2V) communication enable the formation of an electronically coupled platoon [1, 5, 6]. The direct connection between the members of such a platoon leads to a decreased reaction time of about 0.1 seconds, which is significantly faster than the reaction time of a driver of about 2.5 seconds [1, 2, 5–8]. It is thereby possible to reduce the headways within the platoon. The intra-platoon distance between the vehicles is a key performance indicator of the platooning [4].

There have been numerous projects conducted on truck platooning on motorways such as KONVOI, SARTRE and the European Truck Platooning Challenge [1, 9–11]. In the latter, actual truck platoons of 2 to 3 trucks drove on the existing infrastructure in real traffic across Europe. The mentioned projects tested truck platooning on motorways with an average speed of 80 km/h and intra-platoon distance of 10 to 15 m.

However, to the authors' knowledge, there are very limited studies investigating the effects of bus platooning in an urban environment. Compared to trucks running along highways, buses running in urban context have relatively lower cruising speed and stop-and-go driving profiles. Additionally, they are running with both concurrent and conflicting traffic flows and controlled by traffic signals. It is important to evaluate if bus platooning in an urban environment would have positive effects similar to truck platooning along highways.

Therefore, this study evaluates the impacts of bus platooning with respect to energy consumption and traffic flow. The results are based on the Dynamic Autonomous Road Transit (DART) project, by TUMCREATE in Singapore [12, 13]. The project develops a systematic approach to meet the increasing demand for public transport (PT) in large cities, such as Singapore. Similar to other projects [14–17], the DART research project is conducted based on currently available and forthcoming technologies, including electrified buses, level 5 autonomous driving [18] and 5G-based V2V-communication with which allows for an intra-platoon time gap at 0.1 to 0.2 s due to the low communication latency [19]. Such a time gap results in an intra-platoon distance between 1 to 3 m.

B. Public Transport Operation

Today's PT systems, particularly bus operations face many challenges in urban areas. Congestion, traffic signals and varying passenger demand cause irregular travel times on buses [20]. A study [21] shows that traffic signals are the main factors affecting the reliabilities of the bus operations besides the route length. Therefore, traffic signal priorities for buses have become one of the methods for improving the quality of service of the PT systems in urban areas.

In many metropolises, such as Beijing, Shanghai, and Singapore, there are normally only two major PT modes, buses and subways. However, these two systems have a major gap in terms of line capacities [22]. Current practice observed to cope with the demand gap is to dispatch multiple over-lapping bus

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services along major arterial roads. Such an approach leads to a highly dense and frequent bus network in the urban area. Proper PT signal priority is made very challenging to handle at the intersection level with such dense and frequent service network. To tackle this issue, this study proposes the concept of bus platooning with pre-defined plans. With such plans, timetables of different bus lines are coordinated to enable buses to arrive simultaneously and form platoons at the first common stops and travel as platoon along common corridors [23–25]. This bus platooning mechanism reduces the buses' arrival frequencies at intersections and decreases the frequencies of traffic signal priority requests. Therefore, traffic signal prioritisation can be enabled with dense and frequent bus services, and hence help to improve the quality of services of bus operation.

This study aims to investigate the impact of bus platooning on traffic flow and energy consumption. Microscopic traffic simulations are conducted to provide a numeric evaluation of traffic system performance with and without bus platooning. The bus driving profiles generated from the simulations are used for a longitudinal simulation to estimate the vehicle energy consumption in the case with and without bus platooning.

II. Methodology

Figure 1 illustrates the steps of the impact assessment for bus platooning. First, a multi-level operational framework is designed to allow for bus platooning. This operational framework is implemented in a microscopic traffic simulation environment for evaluation of its effects on urban traffic control and quality of flow. Evaluation is conducted for the two scenarios of current bus operation and the platooned bus operation. The evaluation focuses mainly on two aspects, the traffic flow quality and vehicle platoon energy consumption. Detailed methods are explained in the latter part of this section.

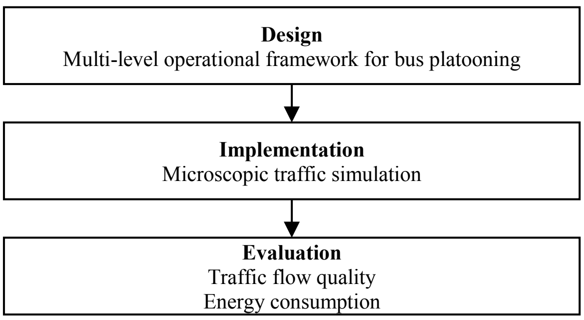

Figure 1: Methodology for Impact Assessment

A. Design

Figure 2 illustrates the procedure of the proposed bus platooning method. When buses from different lines are approaching the first stop along the common corridor, the buses form platoons and travel together. The vehicles may split from the platoon at the intersections to travel to a different direction.

The aforementioned multi-level operational framework is designed consists of three levels: Strategic planning to coordinate timetables of different bus lines, the tactical operation to coordinate buses from different lines in real-time to ensure the planned platooning, and local behaviour to operate individual autonomous buses to realise the platooning.

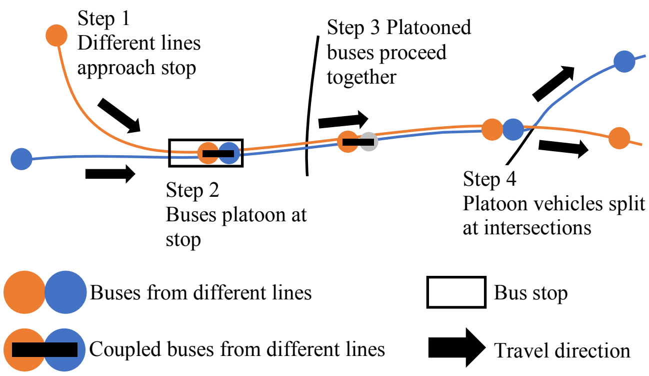

Figure 2: Illustration of Bus Platooning Procedure

The strategic planning level relies on conventional offline public planning methodologies including line alignment and scheduling for each single bus line in the network. As introduced before, the pre-planned bus platooning requires all buses to arrive simultaneously at the first common stop. Therefore, departure times of all lines to be platooned will be adjusted to achieve the synchronised arrival. The strategic planning level delivers the coupling strategies, including bus lines to form platoons as well as the platooning location and time. Such a strategy serves as a basis for tactical operation [23, 24].

Tactical PT operation focuses on the control of the buses' journey after their departure. It aims to coordinate all buses in real-time to ensure the pre-planned platooning. Particularly when buses are dwelling at stops, it examines the necessary dwelling time based on passenger boarding and alighting, as well as the platooning plans. The dwelling times are extended when a bus from another line is late for platooning according to the strategic planning.

Local behaviour focuses on the autonomous driving behaviour of buses. The enhanced intelligent driver model (EIDM) [26] is used and modified as the fundamental car-following model for achieving the bus platooning. However, this driving behaviour is also constrained in terms of acceleration (to 1.5 m/s^2) and deceleration (to -1.5 m/s^2) for passenger comfort considerations [27, 28].

B. Implementation

The operational framework is implemented in a microscopic traffic simulation environment in PTV Vissim to evaluate the effects of bus platooning in an urban environment. As mentioned above, bus platooning reduces the frequency of bus arrival at intersections, which allows for the implementation of signal priorities for dense and frequent bus services. It is expected that bus platooning will increase the level of service of the PT systems, in terms of travel speed and reliability.

In order to examine the performance of the bus platooning in both terms of traffic flow quality and vehicle platoon energy consumption, a microscopic traffic simulation network (Figure 3) with two major signalised intersections (S1 and S2) is modelled based on a real-life situation in Singapore. It has a length of 1.6 km and includes road geometry, traffic demand and traffic signal timings. Real traffic situation during the morning peak hours, including traffic volume and turning ratios, is modelled. During the morning peak hours, the westbound direction is the main traffic direction with major traffic demand.

Two bus operation scenarios are defined. First, the current bus operation is modelled with three parallel bus lines along the east-west road and one bus line along each north-south road. The headway of each bus line varies from four to six minutes based on real-life data and the arrival of different lines are independent of each other. The proposed platooned bus operation is also modelled. Buses from the three lines along the east-west road are platooned together and arrive with a headway of about five minutes. Private traffic enters the network from all six roads at end of the network, and they may turn left, go straight or turn right at each intersection depending on the real-life turning ratios modelled in the network.

In terms of traffic signal control, fixed-time controls are first modelled based on the current scenario in Singapore for both intersections S1 and S2. An analytical study is conducted to investigate the possibility of implementing traffic signal priority for buses at both intersections. If possible, a coordinated traffic signal control method is implemented for only the main traffic direction (westbound).

This simulation model is expected to provide numeric results for the evaluation of the traffic flow quality, in terms of both buses and private vehicles. It also generated bus driving profiles from the two scenarios which will be used as inputs to the evaluation of vehicle energy consumption.

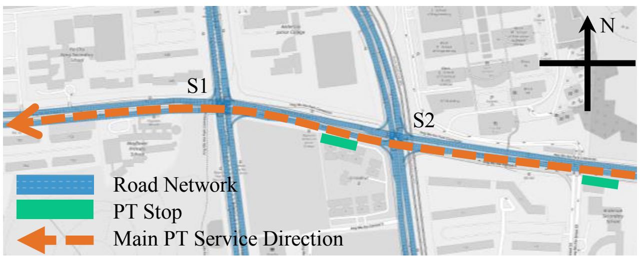

Figure 3: Example Network for Simulating Bus Platooning

C Evaluation

1) Traffic Flow Quality

In order to understand the impact of bus platooning on traffic control, a degree of saturation for PT priorities (Equation 1) is introduced to evaluate the possibility of handling different PT priority request at a certain intersection.

$$DS_{PT} = \sum_{i=1}^{N} \frac{t_c}{H_{i,j}} \cdot \frac{t_{g,j}}{\sum_{h=1}^{M} t_{g,h}} \cdot 100\% \quad (1)$$

where:

DS_{PT} is the degree of saturation for PT priority request at a certain intersection in %;

t_c is the cycle length of the traffic signal in s;

$H_{i,j}$ is the headway of bus i requesting traffic signal stage j for priority in s;

$\frac{t_c}{H_{i,j}}$ refers to the average number of PT priority requests from the i^{th} bus line route per cycle;

$t_{g,j}$ is the green time for traffic signal stage j in s;

$\frac{t_{g,j}}{\sum_{h=1}^{M} t_{g,h}}$ refers to the share of the j^{th} signal stage in a cycle, it is used as the weight of the relevant PT requests.

The traffic signals at both intersections in the example network are running at a cycle time of 142 s with four stages. The signal stages at both intersections are 40 s for the east-west direction and 30 s for the north-south direction. For the current bus operation, the DS_{PT} at both S1 and S2 are 120 % which means the intersections are over-saturated by public transport arrivals. No proper signal prioritisation could be implemented. With bus platoons, the DS_{PT} is reduced to 56 %, which enables the implementation of signal prioritisation for buses. Therefore, in the current bus operation scenario, no traffic signal priority is implemented. But in the bus platoon operation, signal priority is implemented, particularly for the westbound direction as it is the main traffic direction.

30 simulation runs are conducted for each scenario to provide numeric results. Each simulation run lasts for more than 1 simulation hour and contains 30 complete bus journeys along the main direction (10 journeys per bus line). The traffic flow quality of both scenarios using established measurements of effectiveness [29]. For buses, travel speed is calculated to represent the operational speed of buses, travel time standard deviation is calculated to represent the operations' reliability. For private vehicles, the delay and the number of stops at traffic lights per vehicle are also calculated to investigate the impact of bus platooning on general traffic. Additionally, driving profiles (time-speed information) of buses are generated to serve as inputs to vehicle energy consumption estimations.

2) Energy Consumption

To evaluate the energy efficiency of bus platooning, driving profile generated from the two simulation scenarios are extrapolated to provide driving cycles over a distance of 10 km. For the scenario of current bus operation without platooning and signal priority, one driving profile is generated for each of the thee bus lines as shown in Figure 4. For the platooned bus operation with signal priorities, one driving profile is generated for the platooned buses from three lines together. The generated driving profile is shown in Figure 5.

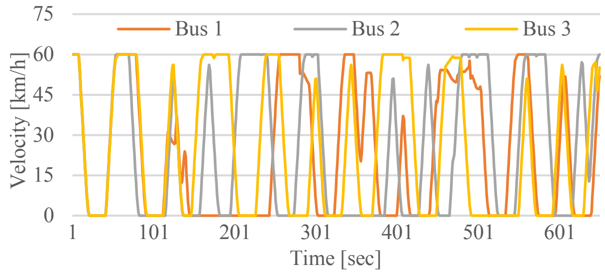

Figure 4: Simulated Driving Cycles without Signal Priority

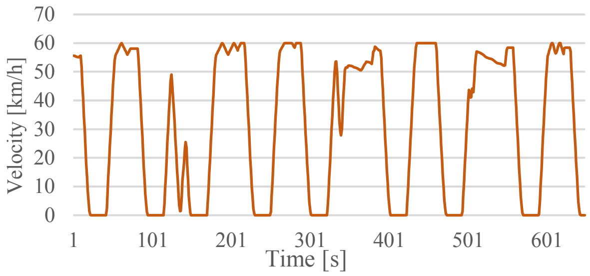

Figure 5: Simulated Driving Cycle with Signal Priority

The important indicators and characteristics of the simulated driving cycles namely average speed, maximum speed, cycle distance, cycle time are presented in TABLE I.

TABLE I. DRIVING CYCLE CHARACTERISTICS

Characteristic	**Value**
Average speed	31.7 km/h
Maximum speed	60 km/h
Cycle Distance	10 km
Cycle time	1045 s

A simple energy consumption model based on a longitudinal dynamics model developed by [30] is used. The model takes rolling resistance, drag resistance, acceleration, battery to wheel efficiency and auxiliary power consumption into account. Combined with the component efficiencies and the power requirements of the auxiliary components such as the air conditioning, the total power consumptions can be calculated. The longitudinal simulation model has a fixed motor, inverter, and transmission efficiencies.

The total resistance encountered by a vehicle is the sum of drag resistance, rolling resistance, gravitational or climbing resistance and acceleration resistance. The only component of the total resistance affected by the platooning is the aerodynamic drag. In addition, at lower velocities, frictional forces dominate, however, with increasing velocity the aerodynamic effects become more important. Therefore, to estimate the impact of platooning on energy consumption, the fraction of the energy used to overcome aerodynamic resistance of the vehicle must be computed. So, other factors such as the shape and frontal area of the vehicle and the number of vehicles in the platoon are to be considered, as these factors influence the aerodynamic behaviour of the vehicle.

The total resistance forces encountered by a vehicle is calculated as shown in Equation 2

$$F_{Total} = F_{Roll} + F_{Drag} + F_{Grad} + F_{Acc} \tag{2}$$

where:

F_{Total} is the total resistance in N;

F_{Drag} is the drag resistance in N;

F_{Acc} is the acceleration resistance in N;

F_{Roll} is the rolling resistance in N;

F_{Grad} is the climbing resistance in N.

The F_{Drag} encountered by a vehicle is calculated as shown in Equation 3

$$F_{Drag} = \frac{1}{2}\rho_{air} {v_v}^2 C_d A_v \tag{3}$$

where:

ρ_{air} is the air density in kg/m^3;

v_v is the velocity of a vehicle in m/sec;

C_d is the drag coefficient of a bus;

A_v is the frontal area of a vehicle in m^2.

The travel time and corresponding velocity have been obtained from the driving cycle. Total power consumption is calculated by Equation 4.

$$P_{Total} = P_{Roll} + P_{Drag} + P_{ACC} + P_{AC} \tag{4}$$

where:

P_{AC} is the power consumption due to air-conditioning in kW;

P_{ACC} is the power consumption due to acceleration in kW;

P_{Drag} is the power consumption due to drag in kW;

P_{Roll} is the power consumption due to rolling in kW;

P_{Total} is the total power consumption in kW.

The input parameters used in the vehicle energy consumption model is shown in TABLE II.

In one of the earliest projects related to vehicle platoons, the PATH program [3] of the University of California, the experiments were performed to study and to estimate the effect of intra-platoon distance and the number of vehicles in a platoon on the average coefficient of drag of the entire pack. Hence, the new drag force on the vehicle is calculated by replacing the original drag co-efficient with the average drag co-efficient of the platoon. Therefore, Equation 3 gets modified as shown in Equation 5.

$$F_{Drag} = \frac{1}{2}\rho_{air} {v_v}^2 C_{d(\mathrm{Avg})} A_v \tag{5}$$

where:

$C_{d(\mathrm{Avg})}$ is the drag coefficient of the bus.

Figure 6 shows the average drag coefficient reduction per vehicle in the platoon as a function of the intra-platoon distance and the number of vehicles in the platoon [5]. The drag coefficient reduction is expressed as the ratio of the average drag coefficient of the platoon to the drag coefficient of a single bus. However, to have more accurate results, computational fluid dynamics simulations of individual buses and platoon have to be performed and analysed.

TABLE II. VEHICLE INPUT PARAMETERS

Characteristics	Unit	Value
Length of vehicle l_v	m	6
m_v	Kg	7000 (with 30 passengers)
No of buses	-	1 to 10
Intra-platoon distance	m	1,2 and 3
$C_{d(\infty)}$	-	0.4
f_r	-	0.008
ρ_{air}	Kg/m^3	1.184
$\eta_{\ motor}$	-	0.908
$\eta_{\ Inverter}$	-	0.945
$\eta_{\ transmission}$	-	0.97
P_{AC}	Kw	3.3
A_v	m^2	7
Driving Cycles	Driving cycle without signal priority (Figure 4)	
	Driving Cycle with signal priority (Figure 5)	

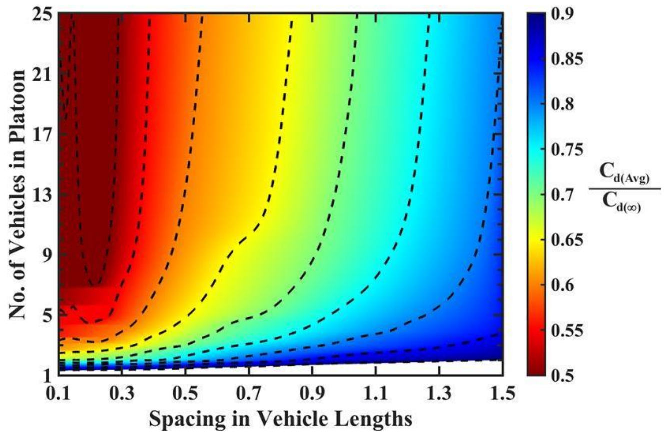

Figure 6: Relation between Drag Reduction Factor, Vehicle Distance and No. of Vehicles in Platoon [5]

The reduction in the drag coefficient of the platoon of buses is shown in Figure 7. In order to evaluate the energy savings due to platooning of buses, three scenarios were considered with the intra-platoon distance of 1 m, 2 m and 3 m. The number of buses in the platoon ranges from 2 buses to 10 buses. The plot shows a reduction in average drag for buses in the platoon. It is evident that the average drag co-efficient of the platoon is decreasing with increase in no. of buses in the platoon. The reduction in coefficient of drag is up to 50% for a platoon of 10 buses with 1 m intra-platoon distance between them. The energy consumption was analysed in four different simulated driving cycles as discussed above (3 simulated driving cycles without signal priority and one simulated driving cycle with signal priority). Hence, 108 simulation runs were performed to analyse the impact of platooning on energy consumption.

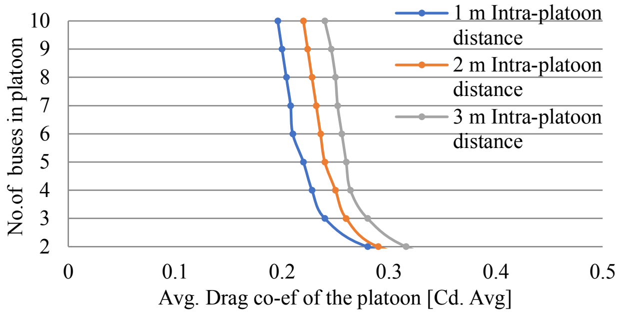

Figure 7: Impact of Platooning on the Drag Coefficient

III. RESULTS

A. Traffic Flow Quality

Both scenarios, with and without signal priority, are simulated to evaluate the performance of bus operation along the westbound direction and the overall network performance for general private vehicles from all directions within the network.

As shown in Figure 8, the platooned bus operation leads to an increment of the average travel speed of buses from 28.2 km/h to 34.3 km/h. Additionally, the travel time standard deviation over the 1.6 km travel distance drops from 37.5 s to 9.4 s, which implies an improvement of the service reliability. Furthermore, the impacts on private vehicles remain similar in both scenarios. The average delay of private vehicles is even slightly reduced (from 55.3 s to 49.9 s) with platooned bus operation with signal priority, as well as the average number of stops per private vehicle (from 1.0 to 0.9).

B. Energy consumption

Based on the experiments, the reduction in drag coefficient results in significant energy savings as there is reduced aerodynamic resistance. The following Figure 9 and Figure 10 show the savings in energy consumption due to platooning in two simulated driving cycles, with signal priority and without signal priority. Figure 9 shows that the energy savings of all the vehicles (up to 10 vehicles) in the platoon with 1 m, 2 m and 3 m intra-platoon distance has an average energy savings of 17.4 %, 15.4 %, 13.7 % respectively.

Figure 10 shows the energy savings of all the vehicles in the platoon (up to 10 vehicles) with 1 m, 2 m and 3 m intra-platoon distances has average energy savings of 12.2 %, 10.7 %, 9.5 % respectively. In addition, from the above plots, it is evident that the energy savings of the platoon are decreasing with increasing no. of buses in the platoon. In addition, the energy consumption of the platoon is minimum when the buses are moving closer to each other.

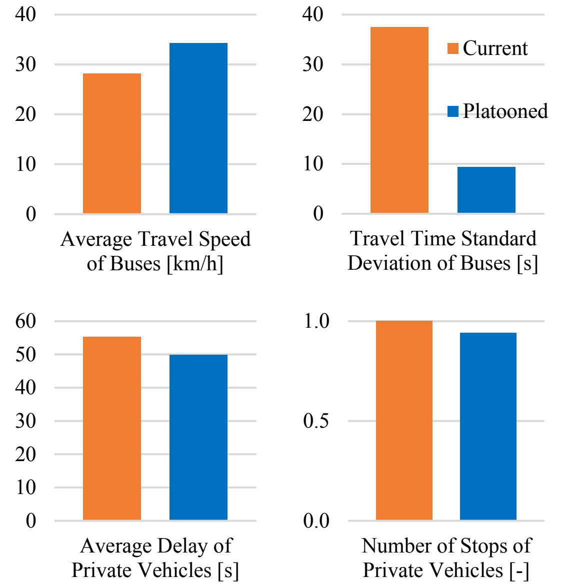

Figure 8: Simulated Performance Comparison between the current Bus Operation and the Platooned Bus Operation

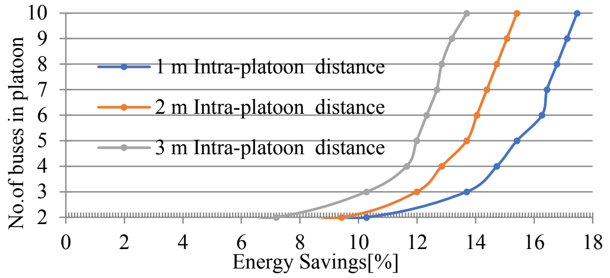

Figure 9: Impact of Platooning on Energy Consumption (Driving-Cycle with Signal Priority)

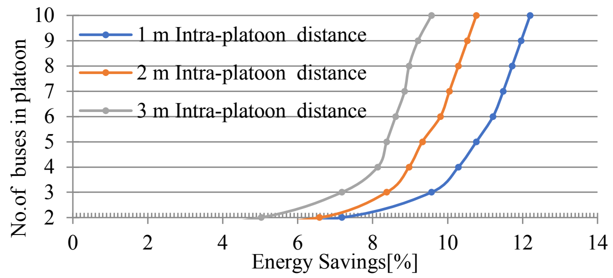

Figure 10: Impact of Platooning on Energy Consumption (Driving-Cycle without Signal Priority)

IV. CONCLUSION

This paper presents a simulation-based study about the effects of bus platooning on traffic flow and energy consumption in an urban environment. The respective impacts were compared for the bus operations with and without platooning.

It is observed that the bus platooning, by organising and reducing the frequency of bus arrivals at intersections, could make signal priority more effective, hence providing a better quality of service, in terms of bus travel speed and service reliability. The simulation also shows that the bus platoon operation with signal priority does not reduce the quality of the traffic flow of private vehicles. It is because the implemented PT priority is with the direction of main traffic demand, hence it will also maintain the quality of traffic flow. However, to fully realise the bus platooning, absolute PT priorities are needed to ensure the simultaneous arrival of buses at stops.

Longitudinal simulation results show that the driving cycle of the bus plays a significant role in energy savings. It can be seen that a 10-bus platoon in driving cycles with signal priority has a cumulative energy savings of 21 % to 25 % when compared to a single bus driving without signal priority. As the reduction in aerodynamic resistance saturates beyond 6 to 7 buses in a platoon, having more than seven buses in the platoon does only yield very limited energy savings. Therefore, operating the platoons with more than 6 or 7 buses has less impact in terms of energy savings. It may have other benefits in terms of traffic volume and congestion, nevertheless, it is necessary to investigate whether the benefits of having more than 6 to 7 buses in the platoon outweighs its operational complexity. Hence platooning of autonomous electric buses in urban environment proves to have a great impact in terms of the energy savings. Further research could investigate the effects of energy savings on the reduction of the battery size, which would in return reduce the overall vehicles costs.

I. ACKNOWLEDGEMENT

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