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Redesigning infrastructure for autonomous vehicles and evaluating its impact on traffic*

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Abstract—Public transport systems, being a safe and sustainable mode of transport, can benefit to a great extent from availing Autonomous vehicle (AV)s. However, the advancements in the road transport infrastructure is not at par with advancements in Intelligent Transportation System (ITS) and vehicle technologies. Cities must consider these changes to realize AVs as a public transport mode. In this paper, we propose three bus-bay designs to integrate AVs with public transport to address this issue. We develop a microscopic traffic simulation model to find the effectiveness of these designs with traffic data obtained from local transport authority and field measurements. The designs are simulated in Singapore city and could be adopted to other cities. Results show that an exclusive AV bay which is physically separated from bus bay reduced the travel time of AV by 5%. Queue length, at the signal near bus stop, has decreased by 27% for such a design.

Index Terms—transport modelling, autonomous vehicles, public transport, shared mobility.

I. INTRODUCTION

Scientists, engineers and policy-makers around the world are working together in making AV a reality. Advances in the field of robotics, high performing computational capabilities and ability to analyze large sets of data are promising for a future with AVs. In addition to that, AVs as a first mile and last mile transport mode [1] can be viable application with a potential for safety and reduced congestion [2]. As the involved industries race to realize AVs, we might witness major infrastructure changes in urban cities. In [3], the authors explore various scenarios of potential autonomous mobility-based transportation with respect to accessibility. They conclude that a significant increase in accessibility can be possible with the use of autonomous vehicles. It mentions that along with the introduction of AVs, infrastructure investments on the same scale might be required for a duration of 15 years. Hence, it is crucial that the stakeholders get a realistic view of necessary changes to make informed decisions. This brings up an underlying question, are the road infrastructural changes in current cities progressing at the same pace of the autonomous vehicle technology? The technological advances in virtual simulation, IoT, AI and machine learning has created myriad opportunities for cities to overcome the complex challenge of urban mobility [4]. For example, in [5], the authors discuss the use of V2X technology with AVs and how the enhanced infrastructure and combination of both technologies (V2X and AV) can increase safety and traffic efficiency. Significant work is

related to AV path planning [6], [7] that focus on shortest path algorithm and path planning in unknown environments can be observed. However, little emphasis is given to the road infrastructural changes to include AVs into existing traffic. In this study, we focus on bus-bay design, a crucial part of the road infrastructure, and measure the impact on AVs and other vehicles with different bus-bay design proposals. We do this by implementing a microscopic traffic simulation model in VISSIM as a virtual environment. Virtual environment offers several advantages for the study of future mobility technologies. It allows simulating different potential landscapes as well as synthetically generated and/or real traffic through collected data. There are varied applications for AV virtual environment simulator. Developing a city model derives its roots from traditional city mapping [8] and combining digital data with spatial and temporal knowledge provides endless simulation possibilities. In [9], the authors have used the virtual environment to model the road surfaces to allow easier road distance calculation. Stephane [10] has developed a model of the virtual urban environment to study the realistic behavior of car drivers and pedestrians and their interaction with each other. Virtual models for transportation sectors have focused on different aspects, ranging from traditional transportation modeling to covering some very specific topics like building textures [11], and lightings. The chosen Area of Interest (AOI) is a residential area, a part of Ang Mo Kio (AMK) district in Singapore, containing major urban elements like Mass Rapid Transit (MRT), bus interchange, schools, parks, public library etc. Approximately, 7 out of 10 use public transport in Singapore [12]. AMK is the eighth most populated district in Singapore and we assume that public transport is fairly utilized in the area. All these factors made AMK a reasonable AOI for this study.

Significant contributions of this paper are summarized below:

- We propose three infrastructure changes in the form of bus bay designs to accommodate AV as a part of public transportation.
- We measure and show the impact of each design on travel time and queue length.

The remainder of this paper is organized as follows. Section II describes proposed bus-bay designs. Section III describes about the simulation model developed for this study. Section IV presents the Key performance indicator (KPI)s that we have used to evaluate the effectiveness of these designs followed by a short discussion. In Section V, we conclude our research and share ideas of future scope.

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II. BUS BAY DESIGNS

Bus bay is a specially constructed area separated from the road and is used for the loading and unloading passengers [13]. Bus bay allows the through traffic to move freely without obstruction from buses stopping at the stops. Bus bays can be considered effective primarily in the parts of road network with high traffic volume or speed such as urban expressways, or in downtown where large number of passengers board and alight. Bus bays can be found almost everywhere in Singapore and also in mega cities such as Hong Kong, Beijing and Tokyo. A bus bay consists of entry, exit and the stopping point where the bus dwells to pick-up and drop-off passengers. The entry and exit areas facilitate a bus to safely enter a bus bay from the shoulder lane and leave the bus bay to merge into traffic on the shoulder lane [14]. Further, we propose three bus-bay designs which are modifications to the existing taxi pick-up or drop-off point or taxi point that we considered for our study. The location of taxi point is shown in Fig. 1. The details of proposed designs are elaborated in the following sub-sections.

A. Proposed Design 1: Shared Bus Bay

In this design, we modify the taxi pick-up and drop-off point to bus bay that is shared by public transport buses as well as AV shuttles. The bay location as indicated in Fig. 1 is modified as shown in Fig. 3(a). The Land Transport Authority of Singapore has suggested length of bus-bay based on passenger volume as shown in Table. I. The bus-bay length is adjusted to 70m which is the mean value of single bus bay (63m) and double bus bay (77m) to accommodate spacing for AV shuttle. In the simulation model, which will be described in detail in section III, the entry and exit links are designed independently.

B. Proposed design 2: Elongated bus bay

Here, we propose a longer bus bay which is extension of the existing bus-bays in Singapore where two buses can stop simultaneously at the bay. Seamless manoeuvre is considered the factor for defining the total length of the bay. For this purpose, a simulation model was used to check if there are any collisions while entering/leaving the bay and a length of 91m was found out to be optimal. This value is indicated in the Table. I.

C. Proposed design 3: Exclusive AV bay

With this design, we propose an exclusive AV bay which is parallel to bay in taxi point and geographically located behind the bus-bay as shown in Fig. 3(c). The length of the bay is equivalent to the bus-bay to accommodate more than one AV shuttle for seamless pick-up and drop-off of passengers. The length of the exclusive bay is same as bus bay for single bus as mentioned in Table. I.

III. DESIGN METHODOLOGY

A. AV Shuttle

The AV shuttle or AV, as we refer to from now on, resembles a mini-van with 12 seats. We envision it to be used as a public transport mode. Within the simulation model, the AV is modelled as a car since a 3-dimensional model was not available.

B. Simulation Model

We developed a microscopic traffic simulation model in VISSIM for this study. The road network layout designed in the model is as in Fig. 5. For each proposed design, no changes except the bus-bay design changes are applied to the model.

1) *Vehicle Input*: The vehicle data for location 1 as shown in Fig. 5 has been collected during morning peak time from 08:00 AM to 09:00 AM. The volume of vehicles passing through the link containing location 1 was recorded 850 vehicles per hour. The manual counting of vehicles at the intersection was done at 5 minute interval. Therefore, we have used a vehicle input of 950 vehicles per hour, after error adjustments, in the simulation model for input I. Input II refers to the buses entering from the bus interchange and the volume is approximated to 120 buses per hour determined from bus headways provided by the local bus operator. Turning ratios at the signal of input I is approximated from the sample counts at the signal as shown in Fig. 5 and for Input II from the bus routes provided by the bus operator. Turning ratio is defined as the proportion of the flow on an incoming road which turns to an outgoing road at the intersection [16]. It is an important parameter because it shows the routing choices and helps in creating a realistic model of the scenario.

2) *Public transport lines*: There is a bus for every seven minutes in the bus stop considered for this study. The same is fed into the model. Impact of autonomous vehicles on traffic flow has been extensively studied for different penetration rates [17] [18]. Gartner forecasts [19] say that there will be nearly double the number of AVs by 2023 as compared to 2020. No research quantified the penetration rate of AVs in public transport to our knowledge. Hence, we have assumed AV shuttle frequency to be half of the frequency of arrival of buses at the same stop and it will operate as a public transport mode. The route for the bus and AV is same where it enters from the north of the road network and leaves the signal as shown in fig. 5.

3) *Traffic signal information*: We received signal plan data of the signal in Fig. 5 from Land Transport Authority, Singapore. Fig. 4 shows the calculated signal plan with an cycle length of 155 seconds from SCATSIM input data.

4) *Pedestrian volume*: It is important to consider the volume of passengers boarding and alighting the buses as it directly effects the dwell time consequently effecting traffic performance indicators like queue length and traffic flow. The capacity of buses ranges from 84 to 139 passengers [20]. Buses with maximum capacity are used in the simulation

Frequency of buses per hour	Bus-bay Type	dimensions
1-39	One single bus-bay	18m (Y1)
40-59	One double bus-bay	32m (Y2)
60-79	One triple bus-bay	46m (Y3)
80-99	Two double bus bays (with 10m separation on the straight kerb)	32m + 32m +10m
100 and above	Two double bus bays (with 10m separation on the straight kerb)	18m+ 46m + 10m

TABLE I
SIZING OF BUS-BAY [15], REFER TO FIG. 2

Fig. 1. 2D and 3D view of the proposed stop obtained from google maps

Fig. 2. Schematic Diagram of Bus Bay in Singapore and Google Earth Image for reference

Fig. 3. Proposed Bus Bay designs with AV bay indicated in red

Fig. 4. Signal plan indicating phases

model because it is considered that double-decked buses are most commonly used during peak hour. de Oña, Juan et al.[21] suggested qualitative method of estimating boarding and alighting passenger volume. Our paper also mentions the lack of match between observed boarding and alighting counts and the lack of passenger alighting data in urban buses systems. Since the proposed location is outside the train station and AOI is a residential area, we assumed that when the bus and shuttle AV arrive at the train station, it is at least 90% full to its capacity and all 100% passengers alight. It is assumed that passengers equivalent to 25% of vehicle capacity board the vehicle at this stop. This assumption is based on regular observations and not with specific data collection.

5) *AV Behaviour*: VISSIM [22] is a lane and space based microscopic modelling and simulation software where behaviour can be defined for individual lane by vehicle type. It has default models for car-following behaviour, lane change behaviour and lateral interaction behaviour. For implementing AV behaviour for our microscopic simulation model, we followed the approach in Co-Exist project [23] where vehicle behaviors are modelled and calibrated based on real-life Vehicle-in-Loop Autonomous Driving System (ADS) testing. We have used the cautious AV model for car-following behavioural model and default values for lane change and lateral behavioural models.

Fig. 6. Average travel time (min)

Fig. 7. Average Queue length (m)

Fig. 5. Road network

IV. RESULTS AND DISCUSSION

In this paper, we aimed to compute the effect of different bus-bay designs on traffic flow. Travel time and queue length are used as measures of effectiveness of each design. Travel time is measured for AV, cars and all vehicles. Since majority of vehicles in the AOI are cars, values are computed separately to find whether they followed the same trend. We ran 50 simulations for each design with a different random seed. Different random seed means different time of vehicle entry into the road network. This is necessary to represent a realistic scenario. Fig. 6 shows that there is a downward trend of AV travel time from Shared bus bay to Exclusive AV bay. Exclusive AV bay has the least travel time for AV. While Exclusive AV bay design looks favourable for AV, more space on street is required to realize such a design. Additionally, upward trend is observed for cars and all vehicles, which include cars, in the same order. All vehicles have higher travel times compared to cars. This is because of the lower acceleration and longer breaking distance of trucks and buses as compared to cars. Trucks and buses are the major vehicles types other than cars in the AOI.

Reduced travel time of AV is a direct benefit for passengers traveling with public transport and using AV as a shuttle

service. However, with decrease in travel time for AVs, the travel time of other cars and traffic increased by 30 seconds between design 1 and design 3 which could be significant considering the scale of the simulation model used for this study. Average queue length for a total of 50 simulation runs for each design is calculated at the signal indicated in Fig. 5. Fig. 7 shows that queue length is larger in Elongated bus bay as compared to Shared bus bay design. It reduced significantly by 27% for Exclusive AV Bay compared to Shared Bus-AV Bay design.

V. CONCLUSION AND FUTURE SCOPE

This paper proposed three bus-bay designs to evaluate the effectiveness of designs when AV is deployed as a public transport mode. A microscopic simulation model is developed in the VISSIM software for this purpose. AV is modelled with a different behaviour as compared to other vehicles in the simulation model. We conclude that physical separation of stopping points for buses and AVs can benefit AVs when operated along with real traffic. This can be observed in the Exclusive AV bay design. This is due to non-interaction of AVs with buses at the entry and exit of bay as compared to the other two designs. While a shared AV bay design performs better for AVs it worsens the travel time of other vehicles. Urban planners and local transport authorities can seek insights from the designs presented in this study.

This study can be extended in future in several directions. It is possible that AV technology might need more priority to be able to operate in the existing road network, in the initial years. Infrastructure changes such as traffic signal priority, dedicated lane might improve AVs when deployed as a public transport mode. These changes can be simulated along with the bus-bay designs proposed. We are curious to evaluate the effectiveness of several such designs possible. The delay propagation of each design in the city level road network is not a part of this study. However it is an interesting direction for future research. Finally, it is interesting to quantify the changes required for such designs as a possible extension of this study.

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