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Environmental Implications of Autonomous Demand Responsive Bus in Microscopic Traffic Simulation

Sangung Park[a], Jooyoung Kim[b,*]

[a]Lyles School of Civil Engineering, Purdue university, USA
[b]Department of Transportation Planning & Management, Korea National University of Transportation, Republic of Korea
jykim@ut.ac.kr

An autonomous demand-responsive transit with mobility-on-demand (MoD) service is an emerging technology to accommodate many travelers with autonomous vehicles (AVs) in congested areas. The MoDA DRT bus can efficiently mitigate the risks of driver fatigue by the frequent routing changes and massive demand induced by the other transportation modes. The MoDA DRT bus has the potential to reduce air pollutants by itself, but less attention has been paid to network-level air pollutant reduction. This paper quantifies the link energy consumption of the road network by introducing the MoDA DRT bus through the microscopic traffic simulation. This paper sets up the four scenarios of different types of MoDA DRT buses to identify the gas emission and electricity consumption in the road network. The results found 8.15 % decrease in CO_2 of the introduction of MoDA DRT bus as well as the environmental impact of the adoption of EVs. The results also showed the importance of relieving the MoDA DRT bus speed limit to maximize the environmental benefits. This study helps policymakers introduce the MoDA DRT bus by considering the environmental impacts of the road network itself.

1. Introduction

Emission estimation from the entities of transportation plays a vital role in mitigating the climate change caused by net greenhouse gas (GHG) emissions. A recent climate change report in 2023 from the intergovernmental panel on climate change (IPCC) has exhibited that GHG emissions from transport emitted 15 % of the net GHG emissions (8.7 Gt CO_{2eq}) (IPCC, 2023). Significantly, the transport sector of net GHG emissions is promising since the sector can be mitigated or reduced by introducing electric vehicles (EVs), compatible engines that the electricity to the internal combustion engine (ICE) by fossil fuels (IPCC, 2023).

EVs come with autonomous vehicles (AVs), one of the successful transportation modes applying automatic driving of the ego vehicle. AVs are known to dramatically decrease the total travel time and provide us the cost-efficient trip (Mahmassani, 2016), accelerating the environmental benefits coming from EVs. Previous studies have shown an increase in the vehicle kilometres travelled (VKT) in the traffic jam area by the large amounts of induced demand due to the convenience of AVs (Basu et al., 2018), contrasting the optimistic view of EVs (Leich and Bischoff, 2019). It implies that introducing AVs with EVs can increase the VKT, emitting more air pollutants.

An autonomous demand-responsive transit with mobility-on-demand (MoD) service is an emerging technology for accommodating many travellers with AVs in congested areas. The MoD-based autonomous DRT (MoDA DRT) bus has (1) flexible routing changes by MoD, (2) autonomous driving, and (3) a higher capacity (maximum 15 people) than that of the general AVs (Park and Kim, 2022). The MoDA DRT bus can efficiently mitigate the risks of driver fatigue by the frequent routing changes and massive demand induced by the other transportation modes.

The MoDA DRT bus is usually driven by electricity, so it is also one of the sustainable transportation modes. Amounts of gas emissions from the road network occupied are significant. Specifically, 371,850 tons of NOx (34.2 %) came from the road network in South Korea in 2019 (Statistics Korea, 2023). Suppose the MoDA DRT bus is successfully introduced. In that case, Gas emissions and air pollutants from the current bus in the road network will be converted only to electricity consumption by the MoDA DRT bus. For example, all-electric vehicles cause 2,817 pounds CO_{2eq}, while gasoline vehicles with ICE emit 12,594 pounds CO_{2eq} per vehicle day, 4.47 times larger than those of all-electric vehicles in the U.S. (McLaren et al., 2016).

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The MoDA DRT bus has the potential to reduce air pollutants by itself, but less attention has been paid to the network-level air pollutant reduction by the MoDA DRT bus. Previous studies focused on the environmental impact of MoDA DRT bus itself (Zhang et al., 2022), but they did not take care of the decrease in air pollutants by introducing MoDA DRT. Previous studies did not compare the scenario of an increase in EVs and AVs due to the induced demand from the conventional bus.

This paper quantifies the energy consumption of the road network by introducing MoDA DRT bus. This paper sets up the four scenarios of different types of MoDA DRT buses to identify the gas emission and electricity consumption in the road network. This paper considers a comparative analysis of the introduction of EVs, MoDA DRT bus, and MoDA DRT bus with increasing the bus speed limit. This paper uses VISSIM, one of the microscopic traffic simulations, to get complete information on the MoDA on the road network. This paper motivates policymakers to introduce the MoDA DRT bus by considering the environmental impacts of the MoDA DRT bus on the road network.

The remainder of this paper is organized as follows: Section 2 describes the methods to analyse the environmental impacts; Section 3 briefly depicts the simulation scenario setup; Section 4 analyses and discusses the environmental impacts by several scenarios; and Section 5 concludes this paper.

2. Methodology

2.1 Data descriptions

This paper selects the Chungju campus of the Korea National University of Transportation and the surrounding area as a study area. This study area surrounds the inner-city bus line no.999, supporting the trips between the university and Chungju City. Note that the inner-city bus is the conventional bus. Thirteen bus stops in bus line no.999 are depicted in Figure 1. The time headway of the bus is 20 min, and two buses are usually in operation. Most of the travelers taking bus no.999 are students. Trip patterns on the inner-city bus line no.999 have the unusual peak hour and unusually high demands on certain stations due to the flexible class schedule. These patterns are suitable for the MoDA DRT bus since the MoDA DRT bus can handle the unusual peak hour and high demands of the MoD service without the driver's fatigue. Figure 1 depicts the study area and the inner-city bus line no.999.

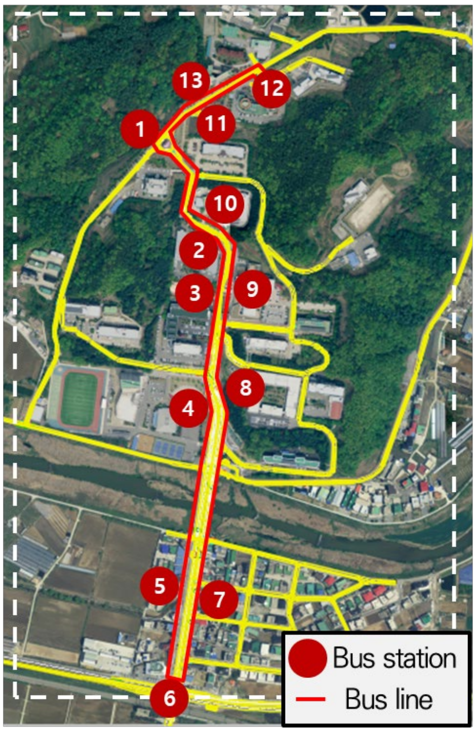

Figure 1: Study area of this study.

2.2 Methodological flowchart

Figure 2 depicts the methodological flows of this study. First, data input comes with the road network and average vehicle speed, vehicle flow data, current bus demand, and bus stop information. Second, by VISSIM, this paper simulates vehicle trajectories and traffic signals considering the conventional or MoDA DRT bus in this area. COM, a VISSIM plug-in, empowers the simulation of the new functions of the MoDA DRT bus from the Q-learning, one of the basic reinforcement learning methods, by the Python environment. From the vehicle, trajectories gathered from VISSIM, network performance, and air pollutants are estimated. We compared four scenarios to be set up in Section 3. We will compare the four scenarios' road network performance and air pollutants.

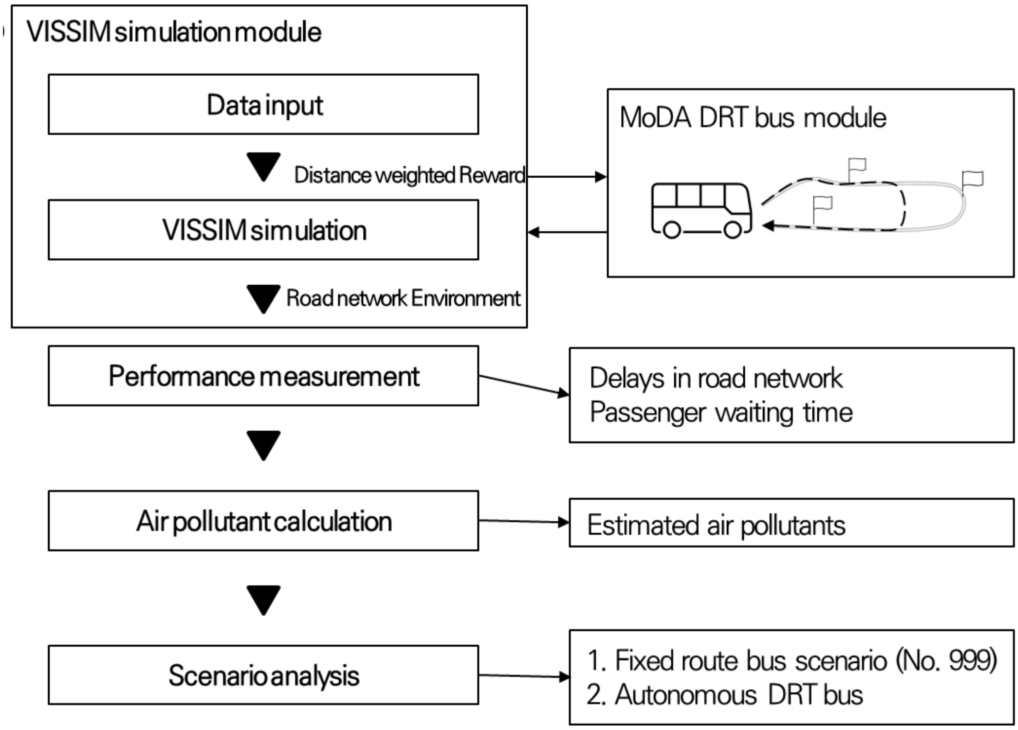

Figure 2: Methodological flowchart of this study.

2.3 Microscopic traffic simulations with the MoDA DRT bus

This paper uses the most famous commercial microscopic traffic simulation, VISSIM made by the PTV group, to calculate the environmental impacts of the road network. COM interface module in VISSIM permits real-time interactions between the Python environments. This study collects vehicle trajectory data to calculate the average link vehicle speed by the types of engines and the vehicle speed threshold. This paper uses the module for the MoDA DRT bus from Park and Kim (2022). The module interacts with VISSIM to simulate the MoDA DRT bus dynamics with bus stops and the bus route updates based on the real-time demands by Q-learning, one of the reinforcement learning methods. Note that there have two main functions of MoDA DRT, autonomous driving and MoD services. This study ignores the improvement of perception-reaction times of the MoDA DRT bus. The speed limit of the MoDA DRT bus is 25 km/h by the current law of the Republic of Korea. For more information regarding the simulation environment and settings, please refer to Park and Kim (2022) and Kim et al. (2022). We run the traffic simulation for 40 min to assess the impact of the MoDA DRT bus.

2.4 Estimation of gas emission and electricity consumption

There are six major air pollutants for calculating the environmental impacts of the road network, carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NO_x), carbon dioxide (CO_2), particulate matter less than 10μm (PM_{10}), and particulate matter less than 2.5 μm ($PM_{2.5}$). To estimate the air pollutants, this study exploits the air pollutant estimation formula of the Greenhouse Gas Inventory & Research Center of Korea in Diesel, Gasoline, LPG (GIR, 2021) and Diesel Bus (NAIR, 2017). The average vehicle speed of each link by the types of engines and the vehicle speed threshold is needed to estimate the six pollutants per kilometer. Table 1 describes the formula from NIER in 2015 by types of engines and air pollutants. Note that 2017 is the latest version of these formulae except for CO_2. Diesel bus has been added to calculate the impact of Table 1 is updated from the previous work by Park et al. (2018).

EVs only consume the electricity for engine power, which means that EVs do not need any estimation of direct air pollutants. This paper considers the indirect air pollutants when power plants generate electricity. This study utilizes the power plant's emissions to calculate the indirect air pollutants. Note that CO_{2eq} can be a single substitute for the overall GHG emissions. Table 2 shows the power plant's emission coefficients. This paper assumes the fuel consumption of an electric vehicle as 5.2 km/kWh, which accounts for the top 20 % of EVs in 2022.

Let Y_{ij} is the air pollutant j from the types of the vehicle engine i, V_i^{ave} is the average link speed by the types of the vehicle engine i, and VKT is vehicle kilometres travelled, and f_{ij} is the equations of the air pollutant j from the types of the vehicle engine i expressed by the Table 1. Overall air pollution estimation is as Eq(1):

$$Y_{ij} = f_{ij}(V_i^{ave}, VKT) \tag{1}$$

GHG emission estimation in electric power sector is calculated with u_j, the use based GHG emission factor, as Eq(2):

$$Y_i = u_j \times VKT \tag{2}$$

Table 1: Emission coefficients considering types of engines by air pollutants (GIR, 2021; NAIR, 2017)

Air pollutants (g/km)	Diesel (40.7 %)	Gasoline (51.4 %)	LPG (7.9 %)	Diesel Bus
CO	$Y = 0.4574V^{-0.5215}$	$Y = (8.336E-05)V^2 - 0.0059V + 0.1871$	$V \leq 79.6\ km/h: Y = 0.6374V^{-0.7666}$ $V > 79.6\ km/h: Y = (4.1425E-16)V^{7.2766}$	$Y = 11.4415V^{-0.803}$
VOC	$Y = 0.1300V^{-0.7265}$	$V \leq 65.4\ km/h: Y = 0.0501 \times V^{-1.0484}$ $V > 65.4\ km/h: Y = (1.05E-06)V^2 - (1.4890E-04)V + 0.0061$	$V \leq 79.6\ km/h: Y = 0.0879V^{-1.0745}$ $V > 79.6\ km/h: Y = (8.2667E-16)V^{6.2696}$	$Y = 0.6774V^{-0.8321}$
NO_x	$Y = 2.7702V^{-0.3869}$	$Y = (-2.9823E-06)V^2 + (2.8119E-04)V + 0.0095$	$Y = (-3.4453E-06)V^2 + (5.1680E-04)V + 0.0047$	$Y = 112.1229V^{-1.6}$
CO_2	$V \leq 65.4\ km/h: Y = 1037.3974V^{-0.5800}$ $V > 65.4\ km/h: Y = 0.0133V^2 - 1.3612V + 129.4859$	$V \leq 65.4\ km/h: Y = 1256.0382V^{-0.5914}$ $V > 65.4\ km/h: Y = 0.0252V^2 - 3.7270V + 245.9051$	$V \leq 65.4\ km/h: Y = 1223.8670V^{-0.6046}$ $V > 65.4\ km/h: Y = 0.0188V^2 - 2.7902V + 203.7804$	$V \leq 65km/h: Y = 264.4900 + \frac{2879.7277}{V}$ $V > 65km/h: Y = 1.3266V + 201.4001$
GDI-PM_{10}	$V \leq 65.4\ km/h: Y = 0.0225V^{-0.7264}$ $V > 65.4\ km/h: Y = 0.0009V^{0.0416}$	$V \leq 85\ km/h: 0.0010$ $V > 85\ km/h: 0.0025$	$V \leq 85\ km/h: 0.0002$ $V > 85\ km/h: 0.0005$	$Y = 0.0363V^{-0.4727}$
GDI-$PM_{2.5}$	$V \leq 65.4km/h: Y = 0.0225kV^{-0.7264}$ $V > 65.4km/h: Y = 0.0009kV^{0.0416}$	$V \leq 85\ km/h: 0.0010k$ $V > 85\ km/h: 0.0025k$	$V \leq 85\ km/h: 0.0002k$ $V > 85\ km/h: 0.0005k$	$Y = 0.0363kV^{-0.472}$

* V: speed of car(km/h), Y: Air pollutant coefficient(g/km), k=0.92

Table 2: GHG emission factor in electric power sector (GIR, 2021)

	Year	tCO_2eq/MWh	tCO_2/MWh	$kgCH_4$/MWh	kgN_2O/MWh
2021	Produce based	0.4434	0.4403	0.0116	0.0093
	Use based (u_j)	0.4403	0.4747	0.0125	0.0100

3. Scenario setup

This study sets up four scenarios for introducing the MoDA DRT bus to the study area. The first scenario (S1) is the base scenario existing current fixed route bus no.999. The second scenario (S2) deletes the current fixed bus line, and all previous bus passengers will take personal electric vehicles. The third scenario (S3) adopts the MoDA DRT bus with a current speed limit of 25 km/h. Total bus lane is about Note that the third scenario does not adopt the AVs. The last scenario (S4) adopts the MoDA DRT bus with a relieved speed limit of 50 km/h, the same as the current conventional bus.

This paper mainly compares three different combinations, (1) a comparison between S1 and S2 to check the importance of the bus, (2) a comparison between S1 and S3 to check the importance of the MoDA DRT bus, and (3) a comparison between S1 and S4 to verify the significance of relieving the speed limit.

Note that we fix the VKT to compare the vehicle speed impacts equitably. If we do not fix the VKT and increase vehicle speed, a greater number of vehicles in the road network will go through in each simulation time period. It implies that increasing the vehicle speed causes an increase in VKT. However, this study does not consider the induced demand due to increased vehicle speed. Therefore, we should constrain the total VKT as 2,495 km, the result of S1.

4. Results and discussions

Table 3 shows the air pollutants of each scenario. When we delete the current fixed bus line and turn all bus passengers into personal vehicles (S2), all air pollutants are generated by the power plant. When we compare the CO_2 between S2 and S1, the amount of CO_2 increases by 3.54 %. It implies the importance of the bus, although we adopt EVs with or without buses. Second, we compared S3 to S1, and amount of CO_2 slightly increased by 1.38 %. This increase can be explained by the MoDA DRT bus speed limit, which reduces the overall vehicle speed. Note that when we adopt both EVs and MoDA DRT bus, 53.56 % of the CO_2 (211,259.610 g) remained. When we relieve the speed limit of the MoDA DRT bus (S4), we can get an 8.15 % decrease in CO_2, not considering the adoption of AVs.

The air pollutant estimation by the four scenarios implies three points. First, this study asserts the importance of mass transit (bus) regardless of adoption of AVs. When we directly compare two cases in S1 and S2, adopting EVs increases air pollutants in total. This result implies that if we remove the mass transit and compel the usage of AVs, it will lead to severe traffic congestion with a lot of air pollutants coming from AVs. It guides policymakers to keep the public transportation services in the era of EVs beyond autonomous vehicles.

Second, this study explains the environmental advantages of adopting the MoDA DRT bus by comparing S4 to S1. Policymakers will be encouraged to adopt the MoDA DRT bus because of the advantages of environmental benefits, including cost-efficient management and improvement of the overall transportation network performance.

The last point is the importance of the speed limit of the MoDA DRT bus. Although overall VKT is the same, the MoDA DRT bus speed limit distracts the environmental impact of the MoDA DRT bus by comparing S4 to S3. This paper asserts that maximizing the environmental impact of the MoDA DRT bus needs relieving the bus speed limit to 50 km/h or much higher. Overall idea

Table 3: Estimation results of emission and air pollutants (Unit: g)

Air pollutants (g)	S1	S2	S3	S4
CO	197.821	-	199.830	187.853
VOC	13.492	-	13.741	12.052
NO_x	779.428	-	786.153	739.072
CO_2	394,469.410	408,424.881	400,468.415	363,156.387
PM_{10}	3.263	-	3.296	3.069
$PM_{2.5}$	3.002	-	3.032	2.824
CH_4	-	10.755	547.731	912.885
N_2O	-	8.604	0.014	0.024

5. Conclusion

This paper analysed the environmental impacts of the energy consumption of the entities on the road network by adopting the MoDA DRT bus. This paper simulated the study area by using VISSIM with the MoDA DRT bus modules and compared the simulation environment to the original conditions. We collected the vehicle trajectories of each vehicle from VISSIM to estimate the average link speed by type of engine to calculate the air pollutants. This study set up four different scenarios to compare the environmental impact of certain adoption policies. This paper found that the environmental impact of the adoption of EVs is less than the base scenario (S2-S1). This study found the importance of the adoption of MoDA DRT bus implying the environmental impact (S4-S1). Relieving the MoDA DRT bus speed limit is also important to maximize the environmental benefits (S3-S1 and S4-S1).

This study has some limitations. At first, induced demand from the MoDA DRT bus was not considered. The introduction of MoDA DRT is expected to attract personal car drivers. It can reduce the total VKT when we introduce the MoDA DRT bus. It yielded strong assumptions on limiting the VKT. Second, we utilized a fixed ratio of the types of vehicle engines. Many countries and non-governmental organizations warned of the harmful effects of Diesel engines emitting lots of air pollutants. They attempt to change the engines to electricity or other natural gas, which emits fewer air pollutants than Diesel engines. this study used the fixed ratio of the types of engines since there is no reliable prospect of the change of the engines. Third, they do not clearly measure the transmission of electricity. Fourth, we did not quantify the electricity of electric power plants since an amount of electricity usage is relatively low so we do not need to increase electricity generation for an increase in EVs. Current commercial electricity usage of one EV is 6.85 kWh/day based on 5.8 km/kWh. Total electricity usage of Chung-ju si in 2010 April is around 151,443 MWh (DailyCC, 2010). Assume that EV chargers occupy 1 % of the total electricity usage, around 483,870.97 kWh per day on average. 1 % of the electricity generation covers 83,426 VKT, 33 times larger than the base scenario. Note that mean power reserves are 7.7 % of the total electricity. It is sufficiently small to ignore the impact of EV charger.

The next step will apply the reliable prospect of the changes of the engines and apply the same analysis. It reduces air pollutants. Throughout this study, policymakers consider the introduction of the MoDA DRT bus by asserting the environmental benefits and additional indirect benefits of the bus to the road network.

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