Examining the effect of infrastructure features on the energy consumption of diesel and electric buses: A microsimulation-based analysis

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SHORT SUMMARY

The transition from fossil fuel-powered buses to battery-powered buses has been a long process. How to deploy such a mixed bus fleet composed of diesel and electric buses to minimize the energy consumption of transit systems is one of the biggest challenges faced by transit agencies. This study takes an important step in addressing this challenge by investigating the impact of different infrastructure features on the energy consumption of diesel buses and electric buses under a variety of traffic conditions. We leverage a simulated-based approach to generate various transit operating scenarios, and adopt two vehicle activity-based energy consumption models for diesel and electric buses. Preliminary results show that bus stop density has a positive linear effect on the energy consumption of both types of buses. Under congested traffic, diesel buses consume less fuel on dedicated bus lanes, while electric buses achieve energy conservation on regular lanes.

Keywords: energy consumption, diesel bus, transit operation, electric mobility.

1. INTRODUCTION

Oil dependence, climate change, and greenhouse gas health effects are encouraging a shift from fossil fuel-powered buses (e.g., diesel buses) to electric ones (Noel and McCormack, 2014). Considerable efforts have been put into estimating the fuel/energy consumption of diesel buses (DBs) and electric buses (EBs), and understanding their relationship to the operating conditions (Wang et al., 2011, Alam and Hatzopoulou, 2014, Zhang et al., 2014, Gallet et al., 2018, He et al., 2018, Ma et al., 2021). These two types of buses have very different energy consumption patterns. DBs use more energy in congested conditions than in free-flow conditions, while EBs have less energy consumption connected to congested conditions if compared with free-flow conditions (Fiori et al., 2019).

Nowadays, many cities around the world still operate a mixed fleet of buses, including diesel, gas-powered, and electric buses. The deployment of these different types of buses in the city should account for the infrastructure features that optimize their energy consumption and environmental footprint. Previous studies identified that several infrastructure features can significantly influence the energy consumption of DBs and EBs. These include the number of bus stops along the road, the route length, and route grade. Zeng et al., (2015) used GPS and Controller

Area Network data from 153 test buses in Toyota, Japan to predict the trip fuel consumption. They found that the fuel consumption increases linearly with the route length. Kivekas et al., (2017) analyzed the energy consumption variation of EBs caused by driving cycle uncertainty on a specific electric bus route in Espoo, Finland. They observed that the energy consumption is linearly related to the number of bus stops along the route. During the years 2016-2017, Vepsalainen et al., (2018) measured the daily operation data of an EB fleet with six buses in Helsinki and Espoo, Finland, using an Internet of Things system. One of their key findings was that the density of bus stops per kilometer was the most important factor increasing the energy consumption of EBs. Recently, Abdelaty and Mohamed, (2021) and Adbelaty et al., (2021) estimated the significance of the route grade on the consumed energy of EBs. Also, Ma et al., (2021) used high-resolution GPS data of 630 bus routes in Beijing to compare the influential factors on the energy consumption of DBs and EBs. They found DBs are less affected by route characteristics such as the route grade and the average stop spacing compared to EBs. Although these studies have helped us improve our understanding of the relationships between these infrastructure features and the energy consumption of DBs and EBs, they rely on very specific datasets. This limits the generalization of these results (Qi et al., 2018). Moreover, none of these studies investigated different configurations of bus lanes.

We acknowledge there are other factors such as ambient temperature, the initial state of charge, auxiliary systems, the average speed, and driver aggressiveness that can also affect bus energy consumption (Adbelaty et al., 2021, Vepsalainen et al., 2019, Gallet et al., 2018). However, this study aims at investigating and quantifying the relationship between the energy consumption of DBs and EBs and multiple infrastructure features (i.e., supply features) of transit networks under different operating conditions. This is crucial for transit agencies to better deploy mixed bus fleets and for further adoption of fully electric buses in the transit systems.

We classify the infrastructure features into two categories. The first category includes the bus route characteristics, in particular, the density of bus stops per kilometer. The second category considers the bus lane configuration, which includes regular lanes where buses operate in a mixed environment with surrounding traffic, and dedicated bus lanes. In order to generalize the results, we simulate a ring road using the microscopic traffic simulator VISSIM. Energy consumption calculations are conducted using two models: the VT-CPFM (Virginia Tech Comprehensive Power-based Fuel consumption Model) for DBs (Wang et al., 2016), and the vehicle activity-based energy consumption model for EBs (Ma et al., 2021).

The paper is organized as follows. Section 2 describes the general setting of the simulation approach and the mathematical details of the energy consumption models utilized for the DBs and EBs respectively. Section 3 discusses the preliminary results on how the bus stop density influences the energy consumption of DBs and EBs on different lane configurations and network operating conditions. Section 4 outlines the main findings of this paper.

2. METHODOLOGY

We first simulate different network loading scenarios using the microscopic traffic simulator VISSIM, on a 1-km length ring road. In our simulations, we consider dedicated and regular bus lanes. The first subsection describes the network and simulation settings done in VISSIM. We then collect the operation data of buses, and determine their energy consumption. The second and third subsections describe the energy consumption models utilized for DBs and EBs, respectively.

Simulation modeling approach

This paper uses a simulation-based approach to mimic the traffic and transit operating conditions under many possible scenarios reflecting different bus stop densities. The test network consists of a 1-km ring road with two lanes. We distinguish between three operating scenarios. In the first scenario, we set one of the traffic lanes to a dedicated operation. In the second and third scenarios, we consider that buses operate on regular lanes, which means that they have conflicts with the surrounding traffic. For the second scenario, we assume traffic is in a free-flow state. We load vehicles to the network at a constant rate of 35 [veh/h] at the start of the road. For the third scenario, traffic is assumed to be in a congested state. We load vehicles to the network at a constant rate of 150 [veh/h]. In all of these scenarios, we varied the bus stop density between 1 [stop/km] to 9 [stops/km]. The spacing between each two bus stops is the same, i.e., we consider that bus stops are uniformly distributed along the road. For each run, the simulation period is 1 hour, and a single bus with a constant occupancy of 35 persons travels on the ring. The operation data of each bus including second-by-second speed and acceleration are collected and used for the calculation of energy consumption as described in the following two subsections.

Energy consumption model for DBs

Here, we use the Virginia Tech Comprehensive Power-based Fuel Consumption Model (VT-CPFM) to estimate the energy consumption of diesel buses (Wang and Rakha, 2016). The model assumes that the instantaneous energy consumption of a DB is a convex polynomial function of the power when the instantaneous power is positive. The instantaneous fuel consumption remains a constant value when the instantaneous power is negative. The fuel consumption $FC(t)$ [l/s] is determined as:

$$FC(t) = \begin{cases} \alpha_0 + \alpha_1 P_d(t) + \alpha_2 P_d^2(t), \text{if } P_d(t) \geq 0 \\ \alpha_0 \qquad\qquad\qquad\qquad\quad , \text{if } P_d(t) < 0 \end{cases} \tag{1}$$

where $\alpha_0,\ \alpha_1,\ \alpha_2$ are the vehicle-specific model parameters that must calibrated for different vehicles. Due to a lack of fuel economy data for diesel buses, the values of $\alpha_0,\ \alpha_1,\ \alpha_2$ are acquired by averaging the specific parameters in the research of Wang and Rakha (2016).

The term $P_d(t)$ represents the instantaneous power of DB (Kw), which is determined as:

$$P_d(t) = \left(\frac{R(t) + (1+\lambda)M \times a(t)}{3600\eta_d}\right) \times v(t) \tag{2}$$

where M is the weight of buses [kg] which includes bus curb weight and passenger load; $a(t)$ is the instantaneous acceleration [m/s^2]; η_d represents the driveline efficiency, which we set to 0.95 (Gallet et al. 2018); $v(t)$ is the instantaneous speed [km/h]; λ is the mass factor accounting for the inertia of the vehicle's rotating parts, that we set to 0.1 for diesel buses (Gallet et al. 2018). The term $R(t)$ represents the sum of the vehicle resistance forces including the aerodynamic drag force $F_{dr}(t)$, the rolling resistance force $F_{ro}(t)$, and grade resistance force $F_{gr}(t)$:

$$R(t) = F_{dr}(t) + F_{ro}(t) + F_{gr}(t) \tag{3}$$

The drag force is determined as:

$$F_{dr}(t) = \frac{\rho}{25.92} C_d C_h A_f v^2 \tag{4}$$

where ρ is the air density at sea level and a temperature of 15 °C (59 °F) (equal to 1.2256 kg/m^3); C_d is the drag coefficient, which we set C_d to 0.8 (Wang et al., 2016); C_h is the altitude correction factor, which is calculated by 1-0.085 H (H is the altitude in the unit of km); A_f is the bus frontal area, that we set to 6.8493 m^2 for diesel buses based on field data.

The rolling resistance force $F_{ro}(t)$ is:

$$F_{ro}(t) = Mg\frac{C_r}{1000}(c_1 v + c_2) \tag{5}$$

where g is the gravitational acceleration; $C_r,\ c_1,\ c_2$ are rolling resistance coefficients, that we set to 1.25, 0.0328, and 4.575 for diesel buses respectively (Rakha et al., 2001).

The grade resistance force $F_{gr}(t)$ is:

$$F_{gr}(t) = MgG(t) \tag{6}$$

where $G(t)$ is the road grade. In this paper, we set road grade to 0, which leads to $F_{gr}(t) = 0$. Therefore, $R(t)$ only depends on $F_{dr}(t)$ and $F_{ro}(t)$.

For comparative analysis, the fuel consumption unit (l/s) of DB should be converted to the energy consumption unit (Kwh) of EB. According to main energy conversion standard table, 1 L diesel is equivalent to 11.8559 Kwh of electricity (China Energy Statistics Yearbook, 2020).

Energy consumption model for EBs

The energy consumption model proposed by Ma et al., (2021) is adopted to estimate the energy consumption of electric buses. The instantaneous energy consumption *EC(t)* is determined as the sum of the tractive energy $P_{tr}(t)$, and the energy consumed by auxiliary facilities (such as air conditioning, lighting, in-vehicle TVs, etc.) $P_{aux}(t)$:

$$EC(t) = P_{tr}(t) + P_{aux}(t) \tag{7}$$

Following Gallet et al. (2018), we considered a constant 10 Kw for $P_{aux}(t)$.

The tractive energy $P_{tr}(t)$ is determined as:

$$P_{tr}(t) = \eta F_{tr}(t) v(t) \tag{8}$$

where η is the energy loss coefficient factor. When EBs are decelerating or driving down a sufficiently steep slope, regenerative braking system converts and stores partial kinetic energy back to the battery. Therefore, the energy loss coefficient η is different when the tractive force is negative or positive, as shown in Equation (9),

$$\eta = \begin{cases} \frac{1}{\eta_t \eta_{PE} \eta_m} & \text{, if } F_{tr}(t) \geq 0 \\ \eta_t \eta_{PE} \eta_m r_{reg} & \text{, if } F_{tr}(t) < 0 \end{cases} \tag{9}$$

where $\eta_t = 0.97$ is the efficiency factor of the gearbox and transmission system, $\eta_{PE} = 0.95$ is the efficiency factor of the inverter, $\eta_m = 0.91$ is the efficiency factor of the motor, $r_{reg} = 0.6$ is the regeneration factor (Gallet et al., 2018).

The term of $F_{tr}(t)$ represents the tractive force defined as Equation (3) plus the inertial force $F_{in}(t)$:

$$F_{tr}(t) = F_{dr}(t) + F_{ro}(t) + F_{gr}(t) + F_{in}(t) \tag{10}$$

The inertial force $F_{in}(t)$ is determined as:

$$F_{in}(t) = (1 + \lambda)Ma(t) \tag{11}$$

3. RESULTS AND DISCUSSION

Figure 1 depicts the energy consumption of DBs and EBs on regular lanes and dedicated lanes as a function of the number of bus stops evenly distributed along the road. The results are reported for free-flow and congested cases. The energy consumption of DBs and EBs is linearly related to bus stop density. Compared with EBs, DBs are more sensitive to the changes in the number of bus stops. The possible reason could be EBs are less affected by stop-and-go episodes, whereas DB energy consumption increases rapidly under frequent acceleration and deceleration maneuvers. In free-flow traffic, DBs and EBs consume basically the same amount of energy whether they are on regular lanes or dedicated bus lanes. Different results are observed in congested traffic, that is, bus lane configuration shows opposite impacts on the energy consumption of these two bus types. For DBs, dedicated bus lanes can be the road infrastructure that reduces energy consumption. While for EBs, regular lanes show better energy conservation, and the relative difference of energy consumption between regular lanes and dedicated bus lanes gradually increase as the number of bus stops increases. One possible reason is that EBs can convert and store more kinetic energy into electric power through regenerative braking system when driving on interrupted regular lanes with congested traffic and more bus stops. The environmental benefit of EBs on regular lanes comes at the cost of longer travel time, which will reduce the attractiveness of public transport and ultimately lead to the disappearance of the advantage of buses in terms of energy consumption per passenger kilometer.

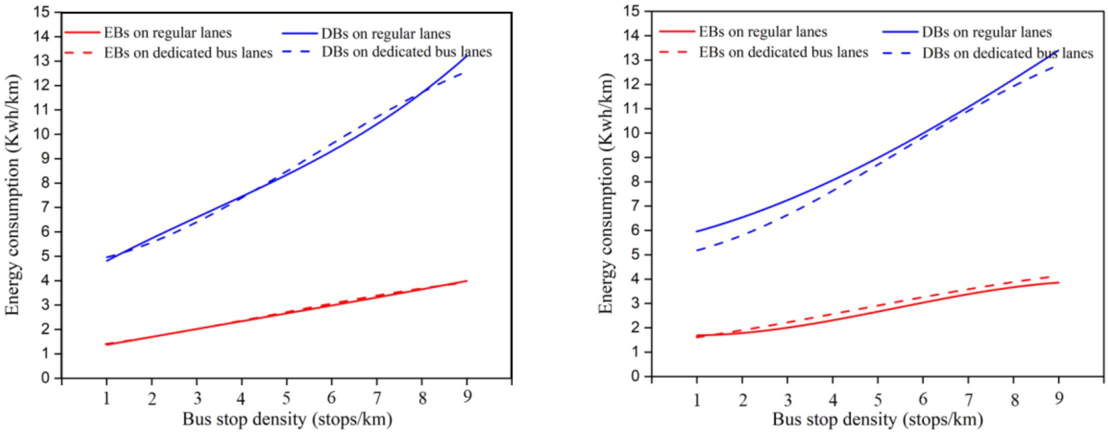

Fig 1. Effects of bus stop density on bus energy consumption under free-flow (left) and congested (right) traffic conditions.

4. CONCLUSIONS

In this study, we leverage a simulation-based approach to investigate and qualitatively depict the impacts of bus stop density on the energy consumption of diesel buses and electric buses on different bus lane configurations and network operating condition. Preliminary results show that the energy consumption of DBs and EBs approximately follows a positive and linear relationship with the number of bus stops per kilometer. In free-flow traffic, energy consumption on regular lanes and dedicated bus lanes are basically the same for both DBs and EBs. Heterogenous behaviors are identified in congested traffic: dedicated bus lanes reduce DB energy consumption, while regular lanes show better energy conservation for EBs. In the follow-up work, more simulations will be conducted for the same bus stop density scenario settings. We also expect to examine the case of uneven distribution of bus stops to complement our study. Moreover, the effect of other infrastructure features such as traffic light conditions (i.e., signal cycle, phase, and effective split) on the energy consumption of DBs and EBs in the network will be investigated.

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