This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Vepsäläinen, Jari

Driving Style Comparison of City Buses: Electric vs. Diesel

Published in:
The 2017 IEEE Vehicle Power and Propulsion Conference (VPPC)

DOI:
[10.1109/VPPC.2017.8330942](https://doi.org/10.1109/VPPC.2017.8330942)

Published: 01/04/2018

Document Version
Peer reviewed version

Please cite the original version:
Vepsäläinen, J. (2018). Driving Style Comparison of City Buses: Electric vs. Diesel. In *The 2017 IEEE Vehicle Power and Propulsion Conference (VPPC)* IEEE. <https://doi.org/10.1109/VPPC.2017.8330942>

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

Driving Style Comparison of City Buses: Electric vs. Diesel

Jari Vepsäläinen
School of Engineering
Aalto University
Espoo, Finland
jari.vepsalainen@aalto.fi

Abstract—The key issues of transportation today are pollution and energy, which both need to be minimized. In addition to the development of emerging technologies such as electric vehicles, reducing unnecessary energy consumption is equally important. This paper focuses on the driving style differences between electric and diesel city buses. The tools used for comparing driving styles are real-world measurements, literature review and driver survey. The study shows that the electric city buses are driven more aggressively and faster on average. The difference is due to electric powertrain's low-level noise feedback and superior power at low speeds.

Keywords—Driving style; Electric vehicle; Powertrain; Statistics

I. INTRODUCTION

All vehicle drivers have their unique driving style. The driving style is affected by traffic, mood, distractions, experience, weather conditions and countless of other factors [1]. By understanding the link between driving style and energy consumption, updated driver instructions, powertrain design and system operation limitations could enhance energy efficiency. Therefore, the focus of this study is on the effect of the powertrain type on the driving style and consumption variation of city buses.

The goal is to investigate differences between the driving styles of electric and diesel city buses. The methods of the study include a review of the related literature, statistical analysis and a driver survey. The survey is conducted in order to elucidate the psychological aspect of driving styles dependence on powertrain type. The statistical tools are implemented to quantify the driving style with comparable factors. The mean and variance of the vehicle velocity are studied throughout the given route while the respective acceleration values are studied for selected snippets after four stops that have potential space for high acceleration. To the best of the author's knowledge, powertrain dependent driving style comparison study between electric and diesel city buses has not been previously conducted.

This paper is structured as follows. First, the driving style state-of-the-art literature is introduced, followed by a comparison of the main characteristics of both electric and diesel powertrains. Next, the simple *longitudinal dynamics model* (LDM) of the city bus is presented. The LDM is used to

estimate the mechanical propulsion energy consumption and the results are compared to complex *electric city bus* (ECB) model. The next section presents the measured driving cycles after which results are examined. The causes of the differences between driving styles are discussed, followed by the conclusions and the summary.

II. STATE-OF-THE-ART

As stated above, many factors influence driving style. The driving style of a city bus is mainly motivated by the need of moving from one stop to another in a given timeframe. In addition to tight schedules, the actions of a bus driver are influenced by the constantly changing status of the surrounding traffic. Therefore, since traffic is interaction depended, the driving style is heavily affected by it. The more time spent on route due to traffic is linearly proportional to the increase in fuel consumption [2]. Therefore, to reduce the effect of traffic variance in driving style comparison, many measurements are performed at different times of the day.

The objective of a driving style analysis can vary but from economic and environmental perspectives, the energy demand variation is key. The acceleration jerks are major cause of energy demand variation [3], while the average speed has little effect on *battery electric vehicle* (BEV) consumption on urban city cycles [4]. However, if the average speed is lowered due to increased number of stops, the energy demand is increased [5]. Aggressive accelerations can account for 10-20 % of fuel consumption increase in urban city buses. However, if the driver strives to achieve calm and determined driving style, up to 15-25 % less energy can be consumed on route [6], [7]. Furthermore, autonomous driving could potentially decrease the energy consumption by 20 %.

If the energy demand is increased by aggressive driving style, what causes aggressiveness? The aggressiveness is shown to be linked to driver age, gender, personality, traffic and the power of the vehicle [8]. In the case of powertrain comparison, it is noteworthy that aggressive driving is more frequent with vehicles that are more powerful. Typically, more power generates more noise, yet the electric drive is quieter than a conventional combustion engine. Moreover, the lack of proper auditory feedback has been shown to affect the driving speed. With lower speed-related noise feedback from the engine, road and environment, the driver tends to

underestimate the vehicle speed [9], [10]. In addition, in a BEV questionnaire carried out by Knowles et al., it was also noted that some drivers thought that the acceleration of the BEV was described as ‘deceptive’ [11].

III. POWERTRAINS

A. Battery Electric

The most common electric drive used in the automotive industry is a *permanent magnet synchronous machine* (PMSM). The PMSM is powered by an electrochemical *energy storage* (ES). Typically, the ES of a city bus is a lithium-ion battery with titanate (LTO) as the anode material [12]. The DC electrical energy from the ES is transformed into three-phase AC power with a power converter, to excite the motor. The power conversion is opposite when the motor regenerates consumed energy while decelerating. Since the PMSM can achieve high torque even at low speeds (Fig. II) a single-speed fixed gear is common, increasing the overall efficiency.

B. Diesel

Even in idle, the *internal combustion engine* (ICE) must constantly rotate to keep itself up and running. Thus, a multispeed manual or automatic transmission is required to convey the power from the motor to the tires. A neutral gear is needed due to the aforementioned idle speed.

C. Comparison

The main components and the energy flow topology for both electric and diesel powertrains is shown in Fig. I. Both of the designs have an ES but the battery pack is more expensive, heavier and larger in volume, due to the inferior energy density [13]. There is no equivalent component for the power converter in the diesel powertrain and the average operating energy loss in the power converter is 5 % [12]. In addition, the charging efficiency of the battery from the main electric grid is usually above 80 % [14], [15]. However, the average energy efficiency of entire ICE diesel powertrain (22 %) is almost three times worse than a BEV powertrain (64 %) [13]. Electric drives are also more silent than combustion engines due to the missing combustion process and the simpler mechanical construction.

Fig. I Main components of the electric and diesel powertrains.

Fig II. Speed-torque characteristics of both electric PMSM and conventional ICE (200 kW machines). Estimation made from [16].

Furthermore, the PMSM and the ICE have almost the opposite speed-torque behavior, as shown in Fig. II. The PMSM can operate from zero rpm with nearly peak torque. The region where the PMSM torque is radically lowered is called a field weakening region, where the magnetic flux field is reduced to reach high speeds without the increase of input power. On the contrary, the ICE requires high speed to achieve its maximum torque. However, since the ICE is coupled with a manual or automatic transmission, the speed zone for the required torque can be achieved at most driving speeds. The transmission can reduce the speed-torque differences between the powertrains to the momentary gear shifts of the ICE powertrain, when no power is applied.

IV. SIMULATION MODELS

To compare the mechanical energy consumption of the two powertrains, the *longitudinal dynamics model* (LDM) of the city bus is presented. The bus design is identical in both cases for the sake of comparison and only the energy required for traction is of interest. The nominal parameters of the bus are shown in Table I.

TABLE I. Nominal parameters of the compared buses.

Parameter	Unit	Value	Symbol
Mass	kg	12400	m
Frontal Area	m ²	6.2	A
Rolling resistance coefficient	-	0.008	f_r
Drag coefficient	-	0.493	C_d
Air density	kg/m ³	1.2	ρ

The forward movement kinematics of the vehicle LDM are governed by

$$E_{mp} = d/3600 \cdot (m \cdot g \cdot f_r + 1/2 \cdot \rho \cdot C_d \cdot A \cdot v^2 + m \cdot dv/dt), \quad (1)$$

where E_{mp} is the mechanical propulsion energy required to move the vehicle over a set distance d , v is the velocity of the vehicle and g is the gravitational acceleration. Energy regeneration while decelerating the electric bus is not considered, in order to give a fair comparison of the powertrains. However, to give a more accurate view on energy

variation, the driven electric city bus cycles are simulated also with the *electric city bus* (ECB) model. In addition to the LDM, the ECB considers the dynamic physics-based nonlinear behavior of the battery, inverter and the motor [17]. Furthermore, the energy regeneration is applied in ECB while braking in suitable conditions.

V. MEASUREMENTS

A total of 57 city bus cycles were measured. Half of the measurements were performed in October 2016 and the rest in February 2017 to reduce the effect of seasonal weather. All the measurements were driven on the same route, bus line number 11 in Espoo, Finland. The route is operated between Friisilä and Tapiola. Both route directions were studied, with Tapiola-Friisilä denoted as TF and Friisilä-Tapiola as FT. The distribution of measured cycle types is shown in Table II.

TABLE II. Distribution of measured cycles.

Powertrain	Fall	Spring	TF	FT
Electric	13	14	13	14
Diesel	15	15	16	14
Total	28	29	29	28

Fig III. Velocity profiles of the standard Braunschweig cycle, two electric bus cycles and two diesel bus cycles. The electric and diesel cycles were selected randomly from the measured cycles.

As presented in Table II, the measurement distribution between the cycle types (powertrain, season and direction) was quite well balanced. However, there was deviation in the diesel

bus models operating on the Espoo 11 bus route. At the time of the experiments, there was only one model of electric bus operating on the route (Linkker) while diesel buses were represented with four different models (one Volvo and three Scania buses). The diesel buses have also been in service for considerably longer time (10-20 years) than the new electric ones (2-3 years).

The velocity profile data from the route was acquired with a GPS measurement system. A hand-held GPS device tracked the real-time position of the bus. The drivers were not informed about the ongoing study, because that could have affected their attitude and thus their driving style. In Fig. III, the standard driving cycle from Braunschweig, Germany is shown in comparison with randomly selected two electric and two diesel bus cycles.

VI. DRIVER SURVEY

A driver survey was carried out to understand the driver's perspective on the effect of the powertrain type. The survey had three background information questions (gender, age and driving experience) and three driving related questions:

- 1) Which do you driver faster, electric or diesel bus?
- 2) Which do you accelerate faster, electric or diesel bus?
- 3) Which do you prefer, electric or diesel bus?

In addition to these questions, the drivers were asked to give feedback in general about driving electric buses.

VII. RESULTS

The bus powertrains were compared with a set of driving profile variables of the Braunschweig cycle and the measured average variables are shown in Table IV. The chosen variables were the mean values of average and maximum speeds, accelerations and the estimated mechanical energy consumptions of all the driven cycles. The speeds and consumptions were investigated throughout the route. However, the acceleration was analyzed only on four selected stops. These four stops were selected due to their location in an area with lower traffic density and similar snippets from the Braunschweig data were chosen. With less traffic, the driver has the opportunity to accelerate faster. In Table III, the *EDA%* is the relative difference between the electric and the diesel bus for each measured variable. The relative differences indicate that electric buses are driven faster and more aggressively than diesel buses on average. This behavior results in 10 % higher mechanical energy consumption.

TABLE III. Statistical data of the Braunschweig cycle and the averages over all the measured cycles in Espoo line 11.

Variable	Unit	BW	Electric	Diesel	EDA%
Avg. Speed	[km/h]	22.9	22.8	21.3	-7.0
Max. Speed	[km/h]	58.2	60.8	54.4	-11.8
Acceleration	[m/s ²]	0.74	0.81	0.73	-11.0
Avg. Stops/km	-	2.66	2.33	2.48	+6.0
Avg. Travel time	[min]	1768	1616	1734	+6.8
Avg. Idle time	[%]	26.3	23.5	23.9	+1.7
Consumption	Wh/km	953	992	900	-10.2

An *analysis of variance* (ANOVA) was applied to the selected variables for all measured cycles to determine if there are statistically significant differences between the two powertrains. The confidence level was set to 95 %. The ANOVA tests show that the speed, acceleration and consumption variables discard the null hypothesis. In Fig. IV, box plot of the average speed comparison is displayed. The mechanical propulsion energy consumptions based on the LDM for each measured cycle are shown in Fig. V.

Fig IV. Box plot of the average speed variation in electric and diesel buses.

Fig V. Mechanical propulsion energy consumption of each measured test. Green circles represent electric and brown diesel buses.

The estimated consumption of the dynamic ECB model was between 0.92 kWh/km and 1.29 kWh/km. The boundaries are approximately proportional to the LDM model, with 10 % higher output values. The difference is due to dynamic losses of the inverter, motor and the battery. It can be noted that these dynamic losses caused by the electric powertrain are quite low. A further in-depth investigation of the model parameters would show which of the input parameters contributes most to the output variation. This investigation is

outside the scope of the study, yet the effect of user input was studied with the driver survey.

Due to the low number of operating electric city buses in the metropolitan area in Finland, only five drivers participated on the driving style survey. Four participants were males and the age range of all participants was 40-65. The driving experience with a city bus ranged from 4 to 10 or more years. The survey questions (1-3) presented previously were answered according to Table V.

Question	Electric	Diesel	Neither
1) Which you drive faster?	0 %	40 %	60 %
2) Which you accelerate faster?	40 %	20 %	40 %
3) Which do you prefer?	40 %	60 %	0 %

The open feedback of the survey mainly focused on the issues regarding the structural inadequacies of the electric city bus design, which is outside the scope of this study. However, one of the participants did mention that he preferred the electric city bus since it was quieter and the acceleration is smoother due to the lack of gearbox.

VIII. DISCUSSION

Based on the measurements and the statistical analysis, the electric buses are driven more aggressively than diesel buses and thus waste more mechanical energy. The average speed on route 7 % less with diesel buses. Although, the diesel buses did stop 7.7 % more often, which could reduce or even out the average speed difference in comparison. The increase in idling time did not increase energy consumption, since only mechanical energy was considered. However, more stops on route require more accelerations, which requires more energy than maintaining a steady speed. Another study showed that every stop on the Espoo 11 route increased the energy consumption by approximately 0.0057 kWh/km in electric city bus operation [18]. Yet, the mechanical energy consumption of electric bus cycles was higher on average, which indicates that the increase is caused by over 10 % higher average maximum speed and average acceleration. When comparing the standard Braunschweig cycle statistics with the averages of the measured cycles, the results are in between the two powertrains. This an expected result and it verifies that the measurements are rational. The Braunschweig cycle results in higher mechanical energy consumption than the diesel average because the average speed is 7.5 % higher even though there are more stops per kilometer on the Braunschweig cycle. To achieve higher average speed with more stops per kilometer on route, higher average acceleration is required. This indicates that the average acceleration of the route (not just on the four selected snippets) is the highest in the Braunschweig cycle.

The box plot of average speed (Fig. IV) shows higher dispersion among the diesel bus cycles than with the electric buses. The wider spread in driving between the powertrain types could be due to the wider age and model distribution of the diesel buses. Interpreting the results, it seems that the

higher average speed results in higher consumption (Fig. V), even though it should be the opposite according de Abreu e Silva et al. [5]. This inconsistency stems from the fact that only mechanical energy is considered in the comparison and the fuel consumption while idling is neglected. The main reason for higher mechanical energy consumption for electric buses is significantly more aggressive accelerations and higher maximum speeds.

The more aggressive driving behavior of electric city buses is most likely caused by lower noise feedback [9]–[11] and higher available power while accelerating [16]. However, the available power depends on the control of momentum and speed, which varies in both powertrains. Due to the low number of participants, the survey results are inconclusive and it can only be stated that based on the data collected, neither the electric nor the diesel buses are solely considered to be driven faster. A more conclusive questionnaire should be carried out once there are more electric city buses and thus more eligible survey participants available.

IX. CONCLUSION

The driving styles of both electric and diesel buses on the Espoo bus line 11 from Tapiola to Friisilä were measured and analyzed. A total of 57 cycles were reviewed, of which 27 were operated with an electric powertrain. The electric buses were driven faster, more aggressively and consumed more mechanical energy on average when compared to diesel ones. The increase in average speed, average maximum speed and acceleration of electric buses results in a 10 % increase in mechanical energy consumption when comparing to diesel buses. Based on previous studies, the main causes are most likely the electric bus's low noise level and high power at low speeds, due to the quiet and efficient performance of the electric motor.

ACKNOWLEDGMENTS

Sincere thanks to Kaarle Patomäki and Joonatan Mahnala who have provided the data of the city bus velocity profiles. The author also acknowledges the financial support from KAUTE Foundation for the research reported in this paper.

REFERENCES

- [1] Z. Constantinescu, C. Marinoiu, M. Vladiu, C. Marinoiu, and M. Vladiu, "Driving Style Analysis Using Data Mining Techniques," *Int. J. Comput. Commun. Control*, vol. V, no. 5, pp. 1841–19836, 2010.
- [2] L. Evans, "Driver Behavior Effects on Fuel Consumption in Urban Driving," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 21, no. 4, pp. 389–398, 1979.
- [3] S. Zorrofi, S. Filizadeh, and P. Zanetel, "A simulation study of the impact of driving patterns and driver behavior on fuel economy of hybrid transit buses," *IEEE Veh. Power Propuls. Conf.*, pp. 572–577, 2009.
- [4] A. Alvarez, F. Serradilla Garcia, J. E. Naranjo, J. J. Anaya, and F. Jimenez, "Modeling the driving behavior of electric vehicles using smartphones and neural networks," *IEEE Intell. Transp. Syst. Mag.*, vol. 6, no. 3, pp. 44–53, 2014.
- [5] J. de Abreu e Silva, F. Moura, B. Garcia, and R. Vargas, "Influential vectors in fuel consumption by an urban bus operator: Bus route, driver behavior or vehicle type?," *Transp. Res. Part D Transp. Environ.*, vol. 38, pp. 94–104, 2015.
- [6] M. Zhou, H. Jin, and W. Wang, "A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing," *Transp. Res. Part D Transp. Environ.*, vol. 49, no. 5, pp. 203–218, 2016.
- [7] A. Lajunen, "Energy-optimal velocity profiles for electric city buses," *IEEE Int. Conf. Autom. Sci. Eng.*, pp. 886–891, 2013.
- [8] B. Krahé and I. Fenske, "Predicting Aggressive Driving Behavior: The Role of Macho Personality, Age, and Power of Car," *Aggress. Behav.*, vol. 28, no. 1, pp. 21–29, 2002.
- [9] M. S. Horswill and A. M. Plooy, "Auditory feedback influences perceived driving speeds," *Perception*, vol. 37, no. 7, pp. 1037–1043, 2008.
- [10] E. Y. nian Wang and E. M. yang Wang, "In-car sound analysis and driving speed estimation using sounds with different frequencies as cues," *Int. J. Ind. Ergon.*, vol. 42, no. 1, pp. 34–40, 2012.
- [11] M. Knowles, H. Scott, and D. Baglee, "The effect of driving style on electric vehicle performance, economy and perception," *Int. J. Electr. Hybrid Veh.*, vol. 4, no. 3, p. 228, 2012.
- [12] M. Pihlatie, S. Kukkonen, T. Halmeaho, V. Karvonen, and N. O. Nylund, "Fully electric city buses - The viable option," *IEEE Int. Electr. Veh. Conf.*, vol. 1, 2014.
- [13] I. J. M. Besselink, P. F. van Oorschot, E. Meinders, and H. Nijmeijer, "Design of an efficient, low weight battery electric vehicle based on a VW Lupo 3L," *25th World Batter. Hybrid Fuel Cell Electr. Veh. Symp. Exhib.*, 2010.
- [14] A. Lajunen and K. Tammi, "Energy consumption and carbon dioxide emission analysis for electric city buses," in *EVS29 Symposium*, 2016, pp. 1–12.
- [15] C. S. N. Shiau, C. Samaras, R. Hauffe, and J. J. Michalek, "Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles," *Energy Policy*, vol. 37, no. 7, pp. 2653–2663, 2009.
- [16] J. Erjavec, *Hybrid, Electric & Fuel-Cell Vehicles*. Cengage Learning, Inc., 2013.
- [17] J. Vepsäläinen and K. Kivekäs, "ECB - a novel dynamic Electric City Bus model." ACRIS - Aalto Current Research Information System. Available: <https://research.aalto.fi/en/datasets/search.html>, Espoo, 2017.
- [18] K. Kivekäs, J. Anttila, K. Tammi, and J. Vepsäläinen, "Influence of driving cycle uncertainty on electric city bus energy consumption," *IEEE Veh. Power Propuls. Conf.*, 2017.