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Analysis of Energy Consumption and Performance of BEV, HEV and an ICEV: A Case Study of Real-Life Road Simulation

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Abstract

Supplying enough power and energy during vehicle operation is one of the key elements in competitive automotive industry. In other words, providing the feeling of smooth operation brings the vehicle a step further when compared to its competitors. So, the main goal behind this research is to examine vehicles with three different powertrain systems and observe their behavior over different drive cycles. Vehicle performances are analyzed under different categories such as consumption (i.e., electricity, fuel), economic perspective, and emission point of view. Since vehicle electrification is a hot topic in Turkey, researchers add a real-life road simulation of Istanbul-Adapazarı Road into perspective alongside regulative drive cycles to try and provide an insight of BEV and HEV behavior, in detail. All three vehicles are modeled on MATLAB/Simulink and the outcomes of simulations are presented in this study.

Key words: Energy consumption, performance analysis, real-life road simulation, vehicle modeling

1. Introduction

When the status in policies and industry are considered, it can be commented that until 2050, global energy consumption and CO_2 emissions will keep increasing due to growth in economy and population since the rise in population will cause more and more oil and natural gas consumption for daily tasks such as transportation and livelihood [1]. For better visualization, the change in CO_2 and greenhouse gasses (GHG) over the recent years are shown in Figure 1 and this paper focuses on management of emission gas production in transportation. As stated in [2], utilization of conventional vehicles leads fossil fuel consumption and unescapable GHG emission. To provide a sustainable transportation option and keep resulting emission levels under the limits, benefitting from renewable energy sources is one of the optimal solutions. Having said that, benefitting from advanced vehicles comes into the picture. Here advanced vehicle technology represents a concept which wraps nonpetroleum based vehicles (i.e., BEVs, FCEVs, and HEVs) under one title [3]. It is a known fact that even energy from renewable sources creates CO_2 and GHG emissions but there are several studies which try to minimize this amount [4,5,6]. In summary, when the global average carbon intensity is considered for power generation on well-to-wheel basis, greenhouse gas represented emissions from battery electric vehicles (BEVs) will continue to be lower than for conventional internal combustion engine vehicles (ICEVs) [7,8,9]. According to [10], electric and hybrid vehicles are critical elements when it comes to development of a healthy environment due

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to their valuable effect on the environment through low CO_2 emission level. By not having an internal combustion engine, BEVs provide driving experience with zero tail pipe emission and most consumers in Europe gravitate towards BEV purchasing. In 2021, over 16.5 million EVs were on the road, this number corresponds to three times of what was used three years before [11]. The visualization of this increase is given in Figure 2.

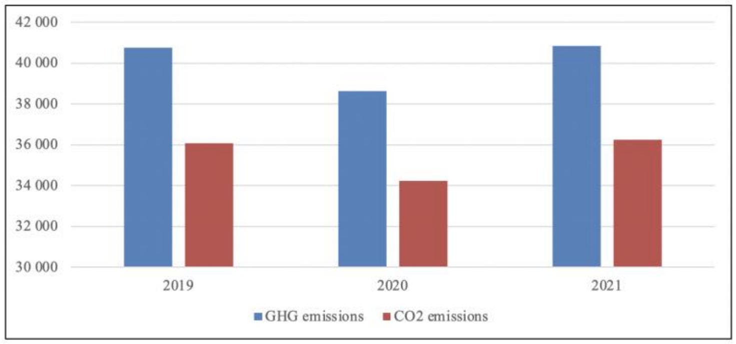

Figure 1. Energy Greenhouse Gas Emissions (Mt CO2eq) [1]

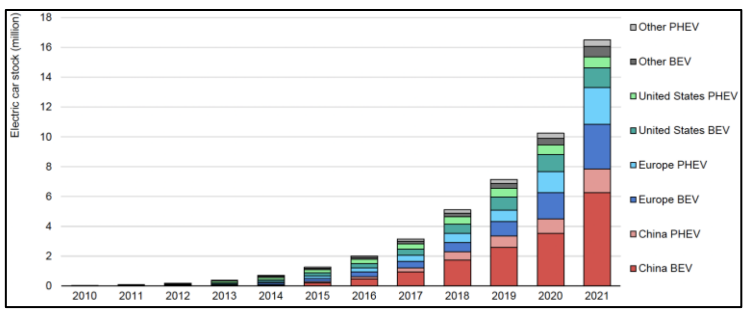

Figure 2. Global EV Usage From 2010 to 2021 [11]

Nevertheless, as written by [12], regardless the low mileage and being environmentally friendly, BEVs are still having hard time in overall sales because of the vehicle range and charging station concerns as well as the higher price values. To overcome range and vehicle charge related apprehensions, there are various studies both in academia and in industry [13,14]. Aside from the current studies on this concept, one of the ways to present advantages of advanced vehicles over the conventional vehicles is to show their performance under the same conditions. Hence, in this novel study, vehicles with three different powertrain systems are considered. Selected vehicle categories are ICEV, HEV and BEV and the representatives of each category have the similar purchasing cost and body types and modeled on MATLAB/Simulink. Driving performances of each vehicle are simulated over a modeled drive cycle on the software. A customized drive cycle between Istanbul and Adapazarı is created from average of six different real-world trip data between these two cities. By feeding road data along with velocity profile to the MATLAB model, calculations for HEV and BEV are held. The goal behind this study is to observe energy usage of vehicles with different powertrains over a fixed route and present the merits of advanced vehicles. Section 1 being this introductory part for our paper, Section 2 provides insight over study methodology. Calculation methods, equations used and modeling rationale behind this study are represented under this chapter. Results acquired through simulations are shared in Section 3 and discussion of these outcomes with brief examples from literature are given in Section 4, Discussion.

2. Materials and Method

2.1. Vehicle modeling

This study examines driving performances of three vehicles with different powertrain systems. Considered vehicles are ICEV, HEV, and a BEV. Consolidated features of them are presented in Table 1, below.

Table 1. Variables of Vehicles

Parameter Name [unit]	BEV	HEV	ICEV
Front Area [m^2]	2.33	2.33	2.31
Number of Tyres	4	4	4
Vehicle Weight [kg]	1650	1720	1360
Aerodynamic Drag Coefficient	0.3	0.3	0.35
Air Density [kg/m^3]		1.25	
Gravity [m/s^2]		9.81	
Road Slope [-]	**not constant**	**not constant**	**not constant**
Vehicle Velocity [m/s]	**not constant**	**not constant**	**not constant**

From Table 1 geometric features and physical conditions for each vehicle can be seen. Modeled HEV had a series hybrid powertrain, and it is a sedan family car. Series HEV structure provided direct drive from the electric motor. As in HEV, considered BEV is also selected as a sedan family car. The notion behind these selections was to provide equality in terms of size and weight. Real world data was collected via ICEV which was a B class SUV. A model for ICEV was not created on Simulink since real consumption data was already acquired via an OBD plug. As the road data yields several hills and valleys, road grade was not assumed as a constant. As the first step of the computations, loads effecting the vehicle performance were calculated. Considered forces were wheel rolling resistance (F_{rr}), air drag resistance (F_{aero}), gravitational force due to grade on the road (F_{slope}) and acceleration forces (F_a). Benefitted equations are presented as:

$$F_{rr} = c_{rr}*m*g*cos\Theta \tag{1}$$

$$F_{aero}= 0.5*c_d*\delta*A_f*V^2 \tag{2}$$

$$F_{slope} = m*g*sin\Theta \tag{3}$$

$$F_a= m*a \tag{4}$$

To sum all the forces acting on the vehicle, the total load on the vehicle is represented with F_T. F_T was calculated as:

$$F_T = F_{rr} + F_{aero} + F_{slope} + F_a \tag{5}$$

For HEV and BEV models, electric energy focused selections were made, as well. For commonization, battery was selected as NCR 18650B type battery of Panasonic for both vehicles. Selected battery has Li-Ion battery chemistry, and it is widely known for its usage in Tesla electric vehicles. It is a known fact that Li-Ion batteries bring higher power density with a smaller design. Battery pack has 345 Volts of nominal voltage [15,16]. It is important to mention that series HEVs are driven directly by electric motors hence engine used in these vehicles behaves as a range extender (REX) hence an elaborate engine model is not studied in this paper.

2.2. Road modeling

Used real life road data was formed as an outcome of six separate trips are held with ICEV between Istanbul and Adapazarı. In each trip, an OBD plug was used to collect road features such as altitude, road slope, velocity, and ICEV fuel consumption. After transferring these inputs into Simulink, data was examined. To summarize the bulk information gathered it can be mentioned that all six trips had large variations in velocity. So, instead of creating one cycle as the summary of all six trips, three separate cycles were formed. The idea behind this decision was to provide a wider insight over the real-life road conditions. In detail, the first one cycle was created with average of values from all six trips, second was with the lowest velocity values of all and the last one was with the highest velocity values of all trips. Velocity profile of each created cycle is given in Figure 3, below. In addition, altitude change between Istanbul and Adapazarı is provided with a screenshot from Google Earth [17] in Figure 4. Acquired altitude data was benefitted during modeling the slope parameter in Simulink.

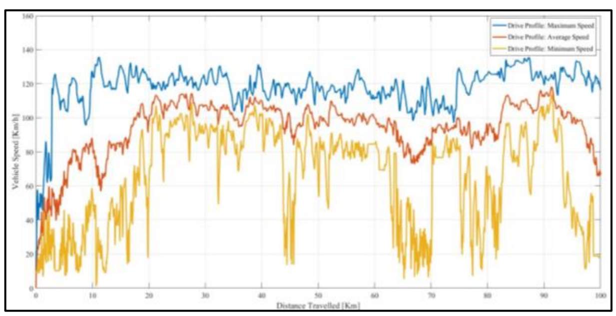

Figure 3. Speed Profile of Each Cycle

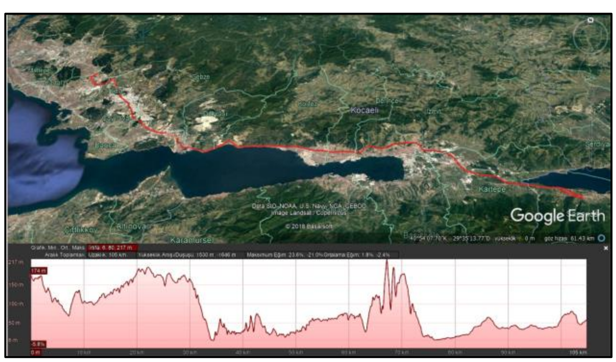

Figure 4. Altitude Change on the Route [17]

3. Results

In this section, outcomes of each drive cycle for ICEV, HEV, BEV will be presented. Results will cover simulation outputs of several case studies.

3.1. ICEV - Real-life data

From Table 2, data gathered from ICEV trips can be observed. Table provides information for each trip in terms of fuel consumption, maximum velocity, and so on. Since simulations for minimum and maximum velocity profiles could not be done for ICEV, only average of six trips could be shared as average cycle results.

Table 2. Results for ICEV

Variables	Trip #1	Trip #2	Trip #3	Trip #4	Trip #5	Trip #6	Average
Max. Speed [km/h]	135.94	122.18	128.50	132.33	131.35	135.41	*130.95*
Avg. Speed [km/h]	84.72	65.16	66.74	86.80	84.23	62.37	*75.00*
Fuel Economy [kpl]	13.16	13.41	12.80	13.39	14.08	13.61	*13.41*
Fuel Consumption [l/100 km]	7.60	7.46	7.81	7.47	7.10	7.35	*7.46*
Travel Duration [min]	75.07	97.61	95.29	73.27	75.51	101.98	*86.46*
Travel Cost [TL]	189.93	187.57	195.28	186.75	177.54	183.71	186.60
Annual Travel Cost [TL]	98,763.60	97,636.40	101,545.60	97,110.00	92,320.80	95,529.20	97,032.00

3.2. HEV - Simulation results

For the simulation of HEV, two separate drive conditions were considered. The first is when driving the vehicle in an environment with losses due to acceleration were exempted. Other one is the case where those losses are included into the scenario. Results retrieved for each case is presented in Table 3. Also, in the table it can be seen that when acceleration is considered, an incrementation in energy consumption occurred.

Table 3. Simulation Results for HEV

Variables	Losses Due to Acceleration Excluded			Losses Due to Acceleration Included		
	Avg. Velocity	*Max. Velocity*	*Min. Velocity*	*Avg. Velocity*	*Max. Velocity*	*Min. Velocity*
Max. Speed [km/h]	118.18	135.66	113.85	118.18	135.66	113.85
Avg. Speed [km/h]	88.56	114.50	41.98	88.60	114.50	41.71
Energy Consumption [kWh]	16.40	21.10	12.46	19.01	24.35	18.44
Energy Consumption [Wh/ km]	164.00	211.00	124.60	190.10	243.50	184.40
Travel Duration [min]	67.74	52.40	143.04	67.74	52.40	143.82
Travel Cost [TL]	58.41	86.15	38.37	75.39	107.02	74.65
Annual Travel Cost [TL]	30,373.85	44,798.65	19,951.10	39,204.75	55,651.05	38,818.65
Cost of Acceleration [%]	-	-	-	29	24	95

During analyses for HEV, the aim was to employ REX as state of charge (SoC) hold. Via this application REX only operated when SoC decreased until a previously decided value (80% in this research) to operate the REX fewer times for a greener mobility. During the computations, assumptions on electricity kWh price and fuel liter were made as 1 kWh electricity is assumed as 1.25 TL and cost of 1 liter of fuel is taken as 25 TL. For each simulation, SoC changes are presented in Figures 5 and 6.

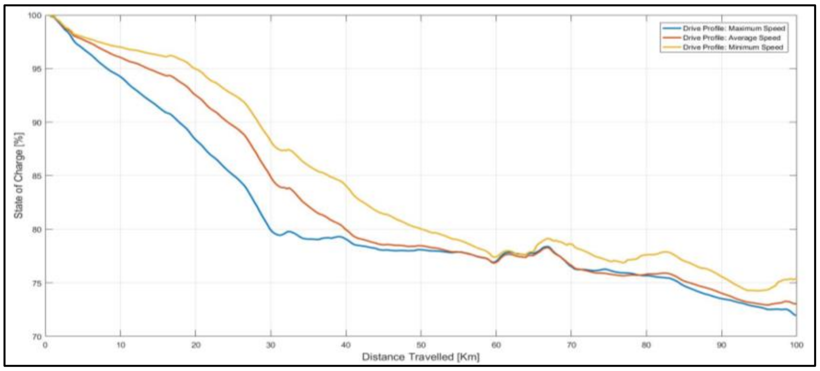

Figure 5. HEV SoC vs. Distance Graph (Acceleration is Exempted)

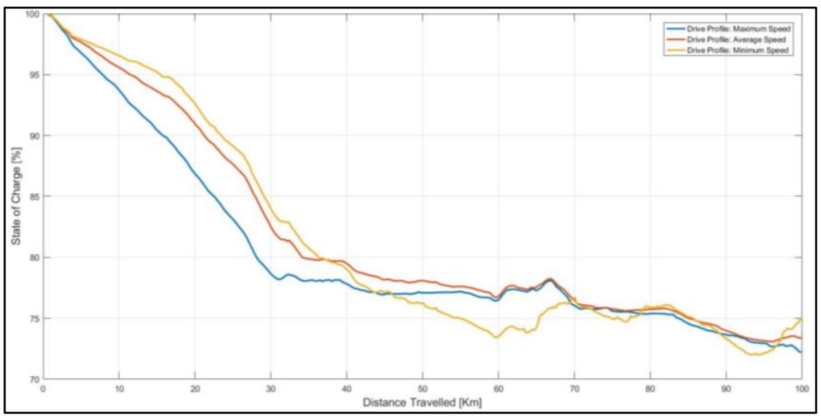

Figure 6. HEV SoC vs. Distance Graph (Acceleration is Included)

3.3. BEV - Simulation results

As in the previous case, BEV is also analysed under two different states (i.e., with and without effect of acceleration).

Table 4. Simulation Results for BEV

Variables	**Losses Due to Acceleration Excluded**			**Losses Due to Acceleration Included**		
	Avg. Velocity	*Max. Velocity*	*Min. Velocity*	*Avg. Velocity*	*Max. Velocity*	*Min. Velocity*
Max. Speed [km/h]	118.18	135.66	113.85	118.18	135.66	113.85
Avg. Speed [km/h]	88.56	114.50	41.98	88.60	114.50	41.71
Energy Consumption [kWh]	16.09	20.77	12.16	18.68	23.91	17.91
Energy Consumption [Wh/ km]	160.90	207.70	121.60	186.80	239.10	179.10
Travel Duration [min]	67.74	52.40	142.90	67.74	52.40	143.82
Travel Cost [TL]	20.11	25.96	15.20	23.35	29.89	22.39
Annual Travel Cost [TL]	10,458.50	13,500.50	7,904.00	12,142.00	15,541.50	11,641.50
Cost of Acceleration [%]	-	-	-	16	15	47

As one can expect travel cost for BEV is lower when compared to other vehicles since there is no fuel usage and electricity is cheaper than fuel. To provide a better comparison, HEV case can be considered. When HEV consumes energy equivalent to 164.00 Wh/km, overall cost of this trip corresponds to 58.41 TL cost. On the other hand, for BEV on the same road, this value is 20.11 TL only.

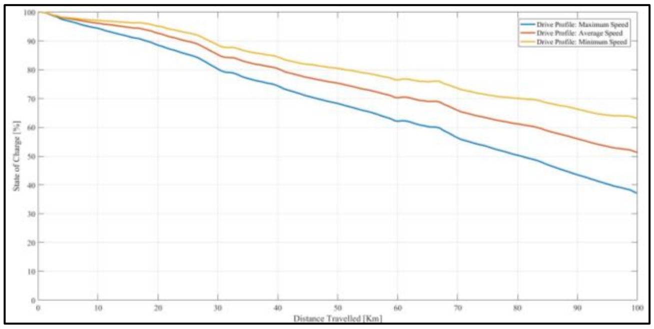

Figure 7. BEV SoC vs. Distance Graph (Acceleration is Exempted)

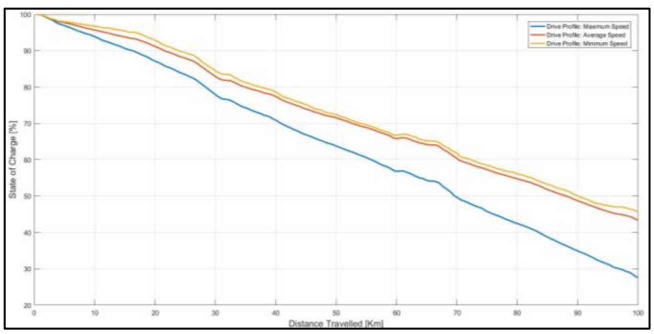

Figure 8. BEV SoC vs. Distance Graph (Acceleration is Included)

3.4. Simulation results for both HEV and BEV when auxiliary loads are added

To extent this examination, auxiliary loads (i.e., air conditioning, heating and so on) were considered. The effect of auxiliary loads was assumed as 500 W. Each simulation was repeated for advanced vehicles under these newer conditions. In contrast to prior analyses, here, only driving with acceleration was considered.

Table 5. Simulation Results for HEV and BEV

Variables	HEV			BEV		
	Avg. Velocity	*Max. Velocity*	*Min. Velocity*	*Avg. Velocity*	*Max. Velocity*	*Min. Velocity*
Max. Speed [km/h]	118.18	135.66	113.85	118.18	135.66	113.85
Avg. Speed [km/h]	88.60	114.50	41.71	88.60	114.50	41.71
Energy Consumption [kWh]	19.64	24.77	19.53	19.20	24.31	18.98
Energy Consumption [Wh/ km]	196.40	247.70	195.30	192.00	243.10	189.80
Travel Duration [min]	67.74	52.40	143.82	67.74	52.40	143.82
Travel Cost [TL]	78.43	109.45	83.78	24.00	30.39	23.73
Annual Travel Cost [TL]	40,784.90	56,915.30	43,566.90	12,480.00	15,801.50	12,337.00
Cost of Acceleration [%]	4	2	12	3	2	6

When table above is observed it can be commented that, by adding the auxiliary loads into the case studies, energy consumption was increased. Nevertheless, energy consumption in BEV was still lower and from economical point of view, it still provided advantages.

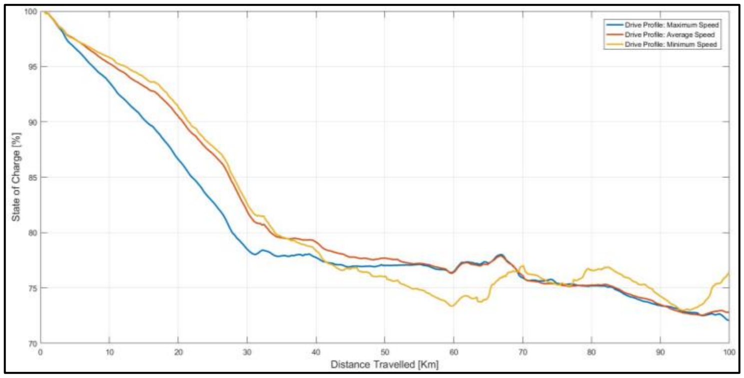

Figure 9. HEV SoC vs. Distance Graph (Auxiliary Loads Included)

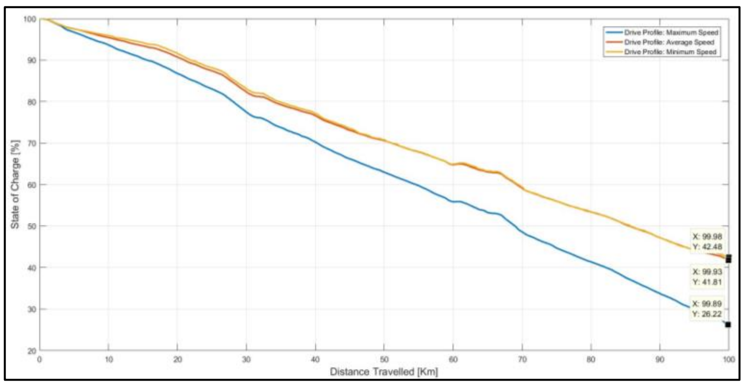

Figure 8. BEV SoC vs. Distance Graph (Auxiliary Loads Included)

4. Discussion

In this study, drive performance of three different vehicles were examined on a customized drive cycle. Through the analyses it can be interpreted that once the electrification in the vehicle increases, a greener and cheaper transportation is acquired. As represented by Kirschtein and Meisel (2015) [18], benefitting from real-life based drive cycles helps getting a view over logistics management and environment friendly transportation. Moreover, this type of application provides examination close to reality. Hereijgers et al. in 2017 [19], analyze vehicles with different powertrains on a real-life route and it is stated that utilizing such a route enables comparison between vehicle performances while creating more reliable results. In 2018, Serin & Albayrak Serin [2], present a comparison between BEV performance on multiple regulative drive cycles as well as a customized one. On this study it is shown that modelled real-life routes are as beneficial as the regulative ones since they too are helpful representing the vehicle behavior and provides a powerful insight. In their study, Sun et al. (2020) [20] focus on three routes from Tianjin and select BEV, fuel cell vehicle (FCEV) and fuel cell hybrid vehicles (FCHEV). Through this study, it is seen that FCHEVs have better performance features on the selected real-life road cycle. Bhatti et al. (2021) [21], state that using real-world drive cycles provide a basis of powertrain simulation as an additional to previously defined drive cycle. As exemplified from current literature, this novel study helps simulating and observing vehicle performance over a real-life cycle and it provides insight over energy consumption of ICEV, HEV and BEV. This can help to see the importance of using advanced vehicles in terms of energy usage and eco-friendly transportation.

Conclusions

To conclude, this paper can be summarized as an effort to simulate performance of vehicles with different powertrain configurations on a customized drive cycle from Turkey. For simulations, three different velocity profiles between to cities (Istanbul and Adapazarı) were created on Simulink. All simulations were carried out for two separate cases (i.e., with and without the losses due to acceleration). To extend the examination, a new case was introduced for HEV and BEV. Here a 500 W auxiliary load was introduced as an HVAC feature to observe its effect over range and consumption of advanced vehicles. In case of auxiliary load, it was seen that despite average velocity being low, due to high travel time, REX operates for a longer time and increases the travel cost and BEV still keeps being a better option.

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