URBAN AND LONG-RANGE DRIVING CYCLE FOR ELECTRIC VEHICLE: A REVIEW

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ABSTRACT

Electric vehicles (EV) according to the definition given by German government and the National Development Plan of Electric Mobility (NEP) consist of all road vehicles that are supplied by an electric motor and particularly get their energy from the power grid which can be recharged externally. There are three types of EV included which are the Range Extended Electric Vehicles (REEV), Plug-in Hybrid Electric Vehicles (PHEV), and the purely electric vehicles (EV). The performance of EV such as the energy and power consumption, and emission can be determined by the means of drive cycles just like for the conventional vehicles. In this paper, the methodology for the development of drive cycles is explained in detail. There are hundreds or even thousands of drive cycles developed all over the world either legislative or non-legislative. We will also be discussing about some of the prominent driving cycles used by international organizations such as the Environmental Protection Agency (EPA) and California Air Research Board (CARB). A total of 15 drive cycles will be covered in this paper covering the rural, urban, and highway areas. The drive cycles are INRETS drive cycle, Indian drive cycle, Manhattan drive cycle, Urban Dynamometer Driving Schedule (UDDS), Representative Non-LA4 (REP05) drive cycle, Highway Fuel Economy Test (HWFET) drive cycle, US06 drive cycle, SC03 drive cycle, BUSTRE drive cycle, ARB02 drive cycle, CLEVELAND drive cycle, Japanese 10-15 mode drive cycle, ECE drive cycle, EUDC, and New European Drive Cycle (NEDC). Heavy duty electric vehicles such as buses are also considered in this paper. For instance, the Manhattan drive cycle is included to represent the driving pattern of buses.

Keywords: *Electric vehicle, drive cycle, traffic pattern, energy consumption, emission*

1.0 INTRODUCTION

Drive cycles are the fundamental tools that can be used to measure the emissions and fuel consumption of vehicles. It can also be utilized to determine the power consumption of electric vehicles. The collected data from actual on-road conditions were used to derive a drive cycle. Usually, these data are presented in a line graph of speed (mph) vs time (min) called the speed profile. It is actually a representation of the driving pattern or conditions in a certain area. Driving cycles are divided into three categories of area being covered. The areas are rural, urban, and lastly highway or main road [1].

We can further classify the drive cycles for rural area driving into eight general classes [1]:

Class 1: average speeds from 60 to 80 km/h with many stops and strong accelerations.
Class 2: long drive cycles with average speed around 100 km/h contain average number of accelerations.
Class 3: the number of stops is higher and the duration is longer. Average speed 20 – 40 km/h with high number of steep accelerations.
Class 4: drive cycles with stable speeds 60 km/h, few stops and low number of accelerations.
Class 5: 120 – 140 km/h high speeds with stops and low accelerations.
Class 6: speeds are high in the range of 100 – 120 km/h but, the number of stops and accelerations
Class 7: no stop together with some fluctuations of low accelerations and the average speed is 80 km/h.
Class 8: the drive cycles' average speeds are 80 – 100 km/h with no stop and low number of accelerations.

Next, we can also classify the drive cycles for urban area driving also into eight general classes [1]:

Class 1: average speeds from 60 to 80 km/h, high frequency of steep accelerations.
Class 2: 40 – 60 km/h average speeds with low accelerations having a few stops.
Class 3: drive cycles with 40 km/h average speed with steep acceleration plus some stops.
Class 4: speeds are from 20 to 40 km/h on average but, the accelerations are strong and plenty.
Class 5: range for average speeds is 80 – 100 km/h which is quite high with intense accelerations.
Class 6: the duration of stops is longer while the speed is low and the accelerations are average.
Class 7: drive cycles having high frequency of weak accelerations and the average speed is around 20 km/h (low).
Class 8: also having 20 km/h average speed with longer duration of stops and many strong accelerations throughout the cycle.

Lastly, the drive cycles for highway driving can be classified into eight general classes too [1]:

Class 1: drive cycles with high speed, around 140 km/h but having low accelerations.
Class 2: long but stable drive cycles having stops, average speed 120 km/h which is still high.
Class 3: 120 km/h speed average drive cycles with high number of accelerations.
Class 4: very high average speed drive cycles.

Class 5: speed is very high but unstable.
Class 6: having speed between 20 to 80 km/h (low speeds) and many stops.
Class 7: also having low speeds between 60 to 100 km/h but with high accelerations.
Class 8: drive cycle with stable low speeds between 80 to 100 km/h.

The accelerating, decelerating, cruising or idling pattern can be obtained from the speed against time profile of the drive cycle. The data for a particular area were acquired by averaging the data of the vehicle's driving pattern when it is driven under the driving pattern and the density of the traffic are the true representation of normal working days [2].

Thus, if the vehicle manufacturers, traffic engineers, environmentalists or, any organizations want to evaluate the performance, power consumption and other characteristics regarding electric vehicle, they are required to have a profound understanding on the existing drive cycles to fully utilize them so that the most appropriate drive cycle can be chosen to fit the purpose in the electric vehicle experimentation.

2.0 DRIVING DIAGRAM AND DRIVING ENERGY CONSUMPTION

Table 1: Group of electric vehicles

Electric vehicle	Definition	Example
Battery Electric Vehicle (BEV) - also called as EVs	- rechargeable batteries with no gasoline - store electricity by high-capacity battery	- BMW i3 - Kia Soul - Tesla X - Toyota Rav4 - Hyundai Ioniq
Plug-in Hybrid Electric Vehicle (PHEV)	- recharge the battery by braking and 'plugging in' - the gas act as assistance to go further	- Chevy Volt - BMW 330e - BMW i8 - Fiat 500e - Toyota Prius
Hybrid Electric Vehicle (HEV)	- powered by both gasoline and electricity - electric energy generated by car's braking	- Toyota Prius Hybrid - Honda Civic Hybrid - Toyota Camry Hybrid

Electric mobility, according to the definition given by German government and the National Development Plan of Electric Mobility (NEP) consist of all road vehicles that are supplied by an electric motor and particularly get their energy from the power grid which can be recharged externally. This includes vehicles that have a combination of electric motor with a small combustion engine such as Range Extended Electric Vehicles (REEV), hybrid vehicles that can be re-energized via the power grid such as Plug-in Hybrid Electric Vehicles (PHEV) and the purely electric vehicles (EV). Other than that, electric vehicle also can be categorized as shown in Table 1.

However, in the context of this paper, electric mobility can be defined as traffic users by driven cars that will contribute to the performance of a more sustainable transportation system, especially matters relating to energy consumption and CO2 emissions. It will more likely to relate all possible factors which can affect the efficiency of vehicles.

The analysis of driving diagram generally related to the nature of a vehicle's speed profile. It has been proved that the driving diagram characteristics can affect conventional vehicles' driving energy consumption and pollutant emission to another high level [3]. Most of the time, the existing driving diagram or also known as driving pattern literature is related to measure the energy consumption by every type of trips. Figure 1 shows the influences and factors of the driving pattern in the context of driving energy consumption. Besides the driving pattern, the nature of the external driving environment such as temperature, humidity visibility, road conditions, road type and road grade also affect consumption directly or indirectly [4]. The drivers' factors such as driver behavior, physical condition, experience, gender and age is another influencing factor that will contribute to the changes of the pattern [5].

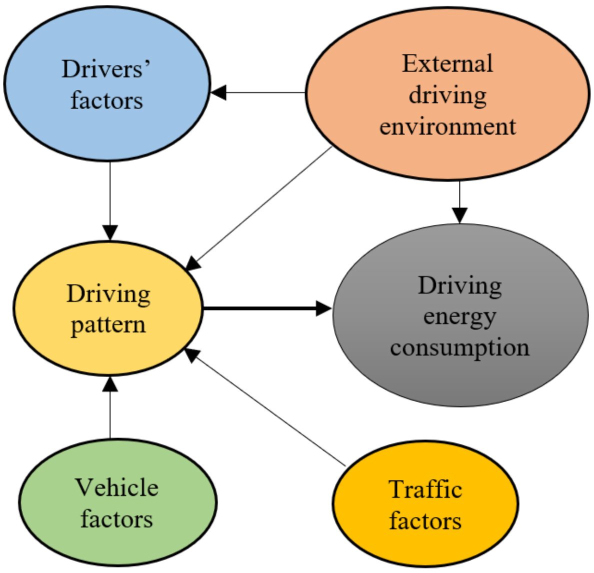

Figure 1: Energy consumption model

At first, the purpose of driving pattern research was to create driving cycles which later will be used for many applications. Either for the investigating and determining of new vehicles' exhaust emissions and consumption levels such as NEDC and INRETS or for research purposes in the way to create model of traffic movements on different places based on elevation of geographical states, different driving environments and types of vehicles [6]. Most of the application of the non-legislative driving cycles is to estimate the pollution and energy consumption for specific areas and trip.

On the type of vehicle sides, driving cycles are utilized for energy consumption and emission modelling [7]. Besides, some research dealing with the recognition of certain driving patterns in purpose to apply appropriate energy management strategies for various driving situations. This kind of motive is particularly applicable for hybrid electric vehicles, which have variety of operating modes [8]. And lastly, the specific driving pattern parameters have been used in the driving behavior analysis and their impact on energy consumption [5].

The mentioned studies of driving patterns largely discuss about internal combustion vehicles (ICVs) or hybrid electric vehicles. However, with the advances in consumer technology of battery electric vehicles (BEVs), driving pattern research should take on a new approach and connection, especially since BEVs have the ability to regenerate energy from braking or decelerating. The regenerated energy from the internal system of the vehicle must take into account since it will not give the right data for driving diagram in context of energy consumption by a vehicle in a trip.

In addition, a limited range of vehicles requires knowledge regarding the factors of energy consumption. The results can help to minimize the usage and to estimate the balance range while driving. This increases the comfort and usability of electric vehicles [9].

3.0 METHODOLOGY

The target of having the driving cycles development was to obtain the best possible representation of the basic data in one representative journey for each domain of usage. There are three areas, which have been defined as targets, are predominantly called as urban driving, rural driving and the highway driving.

The first step to create each driving cycle is by a statistical analysis which aim to determine and define target vectors for the total length, the duration, the proportion of urban to rural driving and the traffic of road used to obtain the best possible representation of the driving data. The following procedure is based on the fundamental methodology that has been used on [10]. With that thirteen further statistical parameters are extracted from the data base to achieve the target criteria and values for the creation of driving cycle. The parameters are determined based on the evaluation of [10] and [11]. A complete overview of the parameters used is given in Table 2.

Table 2: Overview of parameters employed for driving cycles

No.	Parameter	Unit
1.	Average speed	km/h
2.	Average speed > 0	km/h
3.	Average horizontal acceleration	m/s^2
4.	Average horizontal deceleration	m/s^2
5.	Average duration of driving sequences	S
6.	Proportion idling	%
7.	Proportion cruising	%
8.	Proportion creeping	%
9.	Proportion acceleration	%
10.	Proportion deceleration	%
11.	Number of acceleration-deceleration changes	
12.	Root mean square horizontal acceleration	m/s^2
13.	Normal positive acceleration kinetic energy	m/s^2

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The lateral of speed and border acceleration for stop, cruising, creeping, acceleration and deceleration can be found in Table 3. This is the conditions that will specify the of travel graph of a vehicle.

Table 3: Definition of operation modes

Operating mode	Speed v in km/h	Longitudinal acceleration a_x in m/s^2
Stop	0	0
Cruising	> 5	$0,1 \leq a_x \leq 0,1$
Creeping	$0 < v \leq 5$	$-0,1 \leq a_x \leq 0,1$
Acceleration	> 0	> 0,1
Deceleration	> 0	< -0,1

After those statistical analysis, all databases of travelled vehicles are divided into micro-trips. A micro-trip is defined as the phase with a positive driving speed between the two stops as shown in Figure 2 with 5 micro-trips. Every each of micro-trip is constantly linked to stop phase that takes place before it has a realistic idle phase in the cycle.

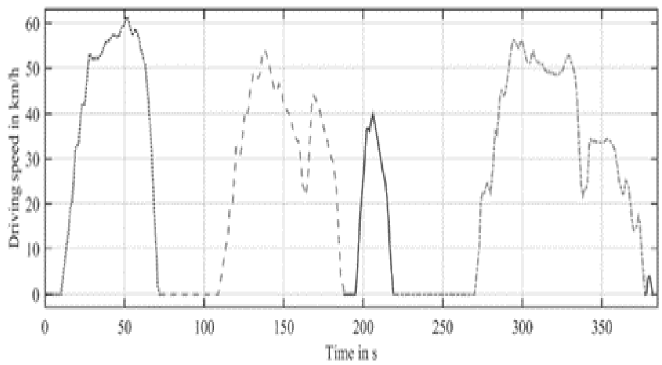


Figure 2: Example of driving sequence with 5 micro-trips

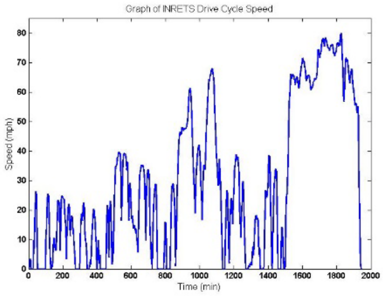
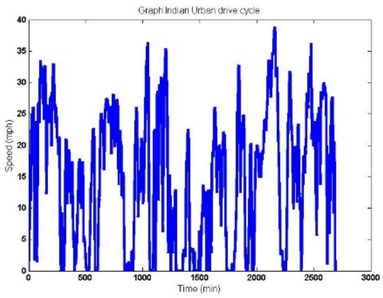
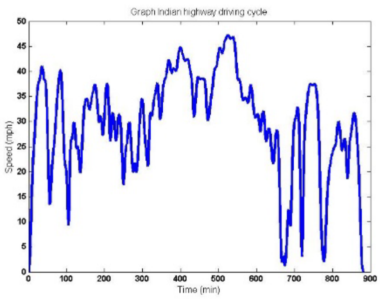
The micro-trip pool is in the next step cleaned to remove strong statistical supporter of outliers. Finally, random combinations of micro-trips with a total statistical set of number of micro-trips has been constructed and all parameters evaluated relative to the target vectors. A large number of combinations are evaluated and compared to find the driving cycle that can represents the best data. This procedure is repeated for each of the three driving cycles with its specific targeted values to get the satisfied pattern [12].

4.0 DATA COLLECTION AND RESULTS

In this paper, there are fifteen type of drive cycle that will be discussed on and seventeen graphs have been plotted by using MATLAB and Simulink software. The constructed drive cycles were

INRETS DC, Indian DC at urban area and highway, Manhattan DC, UDDS, REP05 DC, HWFET DC, US06 DC, SC03 DC, BUSTRE DC, ARB02 DC, CLEVELAND DC, Japanese 10-15 mode DC, ECE DC, EUDC, EUDC for low-powered vehicle and NEDC. All the data was generated by Advance Vehicle Simulator (ADVISOR).

Table 4: Drive cycle and its properties

No.	Name of Drive Cycle	Graph	Area Covered	Speed Range	Average Speed
1.	INRETS Drive Cycle	 **Figure 3:** Graph of INRETS DC	• Urban • Rural • Highway	Max. Speed: 80 mph (128.75 km/h)	28.86 mph (46.45 km/h)
2.	Indian Drive Cycle	 **Figure 4:** Graph of Indian Urban DC	• Urban	Max. Speed: 38.87 mph (62.56 km/h)	14.54 mph (23.4 km/h)
		 **Figure 5:** Graph of Indian Highway DC	• Highway	Max. Speed: 47.22 mph (75.99 km/h)	29.55 mph (47.56 km/h)

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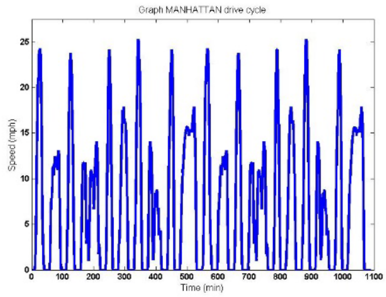
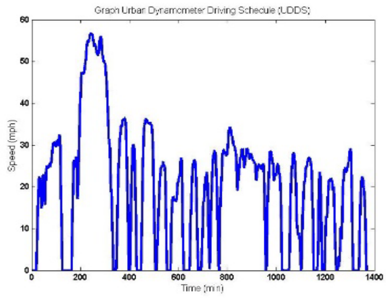
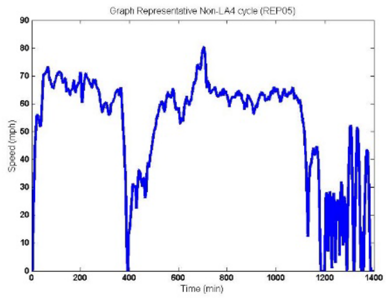
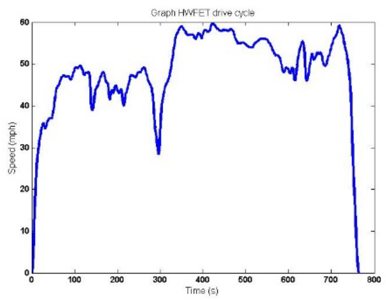
3.	Manhattan DC	 **Figure 6:** Graph of Manhattan DC	• Urban	Max. Speed: 25.3 mph (40.72 km/h)	6.82 mph (10.98 km/h)
4.	Urban Dynamometer Driving Schedule (UDDS)	 **Figure 7:** Graph of UDDS DC	• Urban	Max. Speed: 56.7 mph (91.25 km/h)	19.58 mph (31.51 km/h)
5.	REP05 Drive Cycle	 **Figure 8:** Graph of REP05 DC	• Urban	Max. Speed: 80.3 mph (129.23 km/h)	51.5 mph (82.88 km/h)
6.	HWFET Drive Cycle	 **Figure 9:** Graph of HWFET DC	• Highway	Max. Speed: 59.9 mph (96.4 km/h)	48.2 mph (77.57 km/h)

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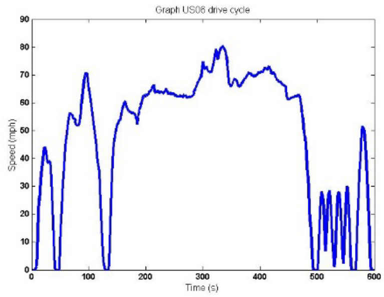
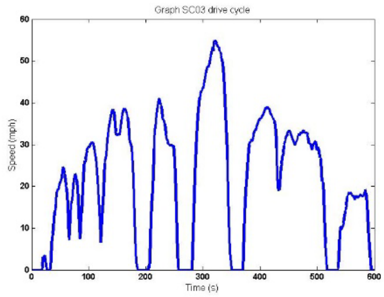
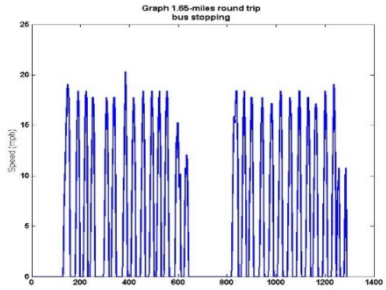
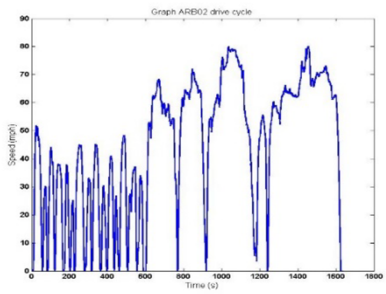
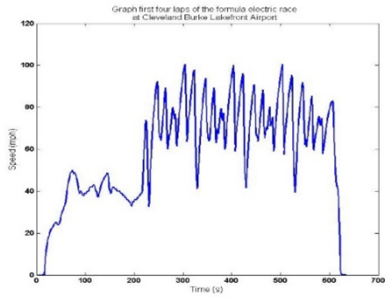
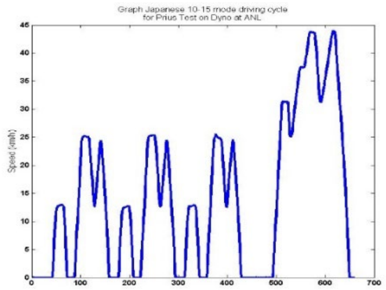
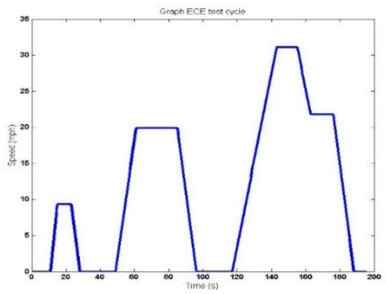
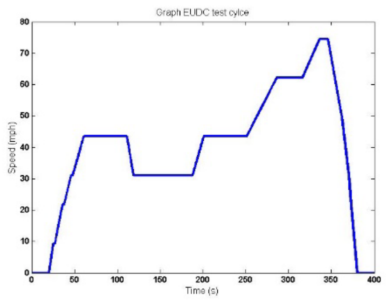
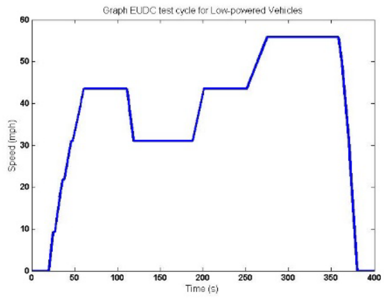
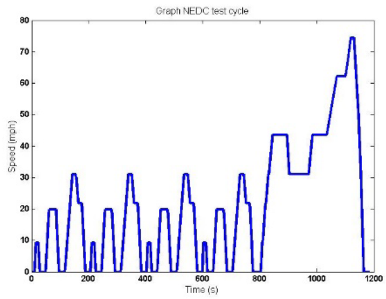
<table>
<tr><td>7.</td><td>US06 Drive Cycle</td><td>
Figure 10: Graph of US06 DC</td><td>• Highway</td><td>Max. Speed: 80.3 mph (129.23 km/h)</td><td>47.97 mph (77.2 km/h)</td></tr>
<tr><td>8.</td><td>SC03 Drive Cycle</td><td>
Figure 11: Graph of SC03 DC</td><td>• Urban</td><td>Max. Speed: 54.8 mph (88.19 km/h)</td><td>21.44 mph (34.5 km/h)</td></tr>
<tr><td>9.</td><td>BUSTRE Drive Cycle</td><td>
Figure 12: Graph of BUSTRE DC</td><td>• Urban</td><td>Max. Speed: 20.31 mph (32.69 km/h)</td><td>4.608 mph (7.4 km/h)</td></tr>
<tr><td>10.</td><td>ARB02 Drive Cycle</td><td>
Figure 13: Graph of ARB02 DC</td><td>• Urban
• Rural</td><td>Max. Speed: 80.3 mph (129.2 km/h)</td><td>43.5 mph (70.0 km/h)</td></tr>
</table>

11.	CLEVELAND Drive Cycle	 **Figure 14:** Graph of Formula Electric Race, CLEVELAND DC	• Racing Lap	Max. Speed: 100.43 mph (161.63 km/h)	57.9 mph (93.2 km/h)
12.	Japanese 10-15 mode Drive Cycle	 **Figure 15:** Graph of Japanese 10-15 for Prius Test DC	• Laboratory	Max. Speed: 43.9626 mph (70.75 km/h)	14.2 mph (22.9 km/h)
13.	ECE Drive Cycle (UDC)	 **Figure 16:** Graph of ECE DC	• Urban • Rural	Max. Speed: 31.0685 mph (49.99 km/h)	11.43 mph (18.4 km/h)
14.	Extra Urban Driving Cycle (EUDC)	 **Figure 17:** Graph of EUDC	• Urban	Max. Speed: 74.62 mph (120.09 km/h)	38.78 mph (62.6 km/h)

		 **Figure 18:** Graph of EUDC for low-powered class vehicles	• Urban	Max. Speed: 55.98 mph (90.09 km/h)	36.97 mph (59.5 km/h)
15.	New European Drive Cycle (NEDC)	 **Figure 19:** Graph of NEDC	• Urban • Rural	Max. Speed: 74.62 mph (120.09 km/h)	20.87 mph (33.6 km/h)

4.1 INRETS drive cycle

INRETS drive cycles were derived by a French institute, INRETS (Institut National de Recherche sur les Transports et leur Sécurité) located in France from the data of actual driving patterns gathered all over Lyon, France [11]. It consists of ten driving cycles for cars each with their respected area covered [1], [11]:

Table 5: Classification of area by INRETS drive cycle

No.	Driving Cycle	Area covered
1.	INRETS urbainlent1	urban
2.	INRETS urbainlent2	urban
3.	INRETS urbainfluide1	urban
4.	INRETS urbainfluide2	urban
5.	INRETS urbainfluide3	urban
6.	INRETS route1	rural
7.	INRETS route2	rural
8.	INRETS route3	rural
9.	INRETS autoroute1	highway
10.	INRETS autoroute2	highway

As shown in Table 5, five of the drive cycles which are INRETS urbainlent1, INRETS urbainlent2, INRETS urbainfluide1, INRETS urbainfluide2, and INRETS urbainfluide3 covered the urban area. In the meantime, three of them which are INRETS route1, INRETS route2, and INRETS route3 deal with the rural area while the last two which are INRETS autoroute1 and INRETS autoroute2 concern with highway or the main roads area [1], [11]. The speed for these two drive cycles are stabilized at an average of 92 km/h. These driving cycles have intrinsic homogeneity in speed levels. Thus, allowing them to describe the driving conditions in detail [1]. Based on Figure 3, the speed range is from 0 to 128.75 km/h while the average speed of the drive cycle is 46.45 km/h.

INRETS drive cycle is among the standard driving cycles used to compare between the proposed vehicle simulator and ADVISOR [13]. Moreover, the INRETS short cycles were developed from the INRETS driving cycles. There are 4 cycles under this program. They are INRETS urbainlentcourt, INRETS urbainfluidecourt, INRETS routecourt (old version), and INRETS routecourt [11]. The first two are for the urban area while the other two are for rural area [11]. These derived driving cycles are short versions of INRETS drive cycles and are useful in measuring the effect of the cold start.

4.2 Indian drive cycle

This driving cycle was developed by the scientists that worked at the Automotive Research Association of India located in Pune, India [2]. It was derived around late 1985 after going through abundance of road tests [2]. The main reason behind the formulation of Indian driving cycle was due to the increasing emission from vehicles that contributes to the pollution of air in India [2]. The emissions are particulars as what can be applied under regulation for diesel engines and also the smoke density or opacity. The unit for opacity is standard Bosch or Hartridge scale while the emissions are expressed in g/kWh as mass emission.

Note that this driving cycle is only valid for two or three wheelers vehicles as these are the usual modes of transportation in the cities of India. According to the data released by the Government of India:

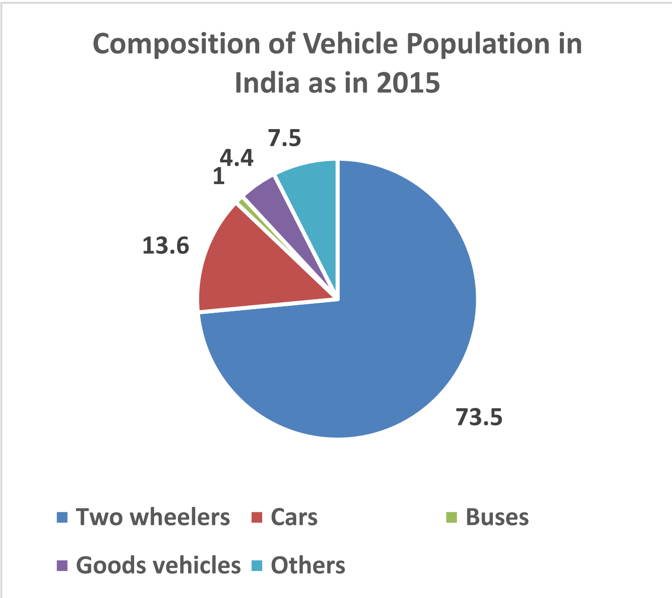


Figure 20: Percentage of vehicle population in India as in 2015

From the pie chart, it was proven that two wheelers make up 73.5% of the vehicle population in India. Follow up next is the percentage of cars which is 13.6%. Good vehicles 4.4% while buses percentage is only 1%. Last but not least, others take up 7.5% of the composition [14]. Even though this data is based on the year 2015, but we can observe the trend of vehicles population in India. On top of that, the traffic situations in India that follow no particular trend results in too many transients in the Indian driving cycle and that is what caused the restriction of only two or three wheelers being made.

In the case for passenger cars, the modified Indian driving cycle is followed. It was based on the European driving cycle but with a modification of lower maximum speed that is applicable for the traffic patterns in India. Also, based on Figure 4 and Figure 5, there are two modified Indian drive cycle. One of them for the urban area and the other one is for highway area. Their speed ranges are 0 – 62.56 km/h and 0 – 75.99 km/h respectively. On the other hand, the average speeds are 23.4 km/h for urban area and 47.56 km/h for highway area.

4.3 Manhattan drive cycle

It is also known as the Manhattan bus cycle because this drive cycle is meant for buses [11]. It is one of the drive cycles under the U.S. cycles program [11]. The development of this drive cycle was based on the actual operation of the transit bus in Manhattan which is one of the five boroughs of New York City with the densest population [15]. One of its purpose is to assess the power management strategy performance of fuel cell-based transit buses [15]. Table 6 below shows the percentage of driving modes for the Manhattan drive cycle:

Table 6: Percentage of driving conditions

Driving modes	Percentage (%)
Idle	34.31
Acceleration	35.41
Deceleration	28.62
Cruise	1.65

Most of the time, the buses were accelerating, decelerating, or went idle [16]. This is predictable as transit buses in the city always make frequent stops. That explains why the cruising percentage is only 1.65% of the trips [16].

As what we can infer from Figure 6, the pattern of the drive cycle is erratic with many steep rises and falls. The reason is the same as what we already explained before, which is due to the travelling conditions of the transit buses. Besides, the area covered is urban as Manhattan itself is a very pulsating city. The speed range of this drive cycle is from 0 to 40.72 km/h and 10.98 km/h on average.

Jerusalem drive cycle is the name of the drive cycle that was derived based on the Manhattan bus cycle by including the movement of buses climbing and descending hill. This is to suit cities that have high traffic density together with some hilly terrains, Jerusalem for an instance. That is where the name came from [17].

4.4 UDDS drive cycle

UDDS stands for Urban Dynamometer Driving Schedule. It was formulated in the 1960's by using data collected on a road route in Los Angeles. This particular driving cycle has many names associated with it. Some other names given are Federal Test Procedure-72 cycle or FTP-72 cycle for short and LA-4 cycle [11]. In Sweden, it is known as A10 drive cycle while Australian refer them as Australian Design Rules (ADR 27) cycle [11]. This drive cycle is one of many cycles under the U.S. cycles program [11]. The type of vehicle that follow this drive cycle are basically light duty vehicles for example, cars [11].

Figure 7 shows that UDDS drive cycle has an average speed of 31.51 km/h and its speed range is from 0 to 91.25 km/h. The type of area covered is urban area. This driving cycle is one of the standard driving cycles that are used for comparing the dynamic vehicle simulator with ADVISOR [13]. U.S. Environmental Protection Agency (EPA) does use UDDS to determine energy or fuel consumption, pollutant emissions levels, and the electric range of light duty vehicles [18].

UDDS have two phases, the first phase is a cold-start for 505 seconds known as bag1. Next phase is a hot-transient phase for 870 seconds known as bag 2. If we add a third phase which is identical to the first phase, known as a hot-start (bag 3) also for 505 seconds, we will get a different type of drive cycle. This drive cycle is called FTP-75 which is also used by EPA.
There is also UDDS for heavy-duty vehicles or cycle D [11]. Although the name is quite similar but, actually it is a completely different drive cycle as HD-UDDS is for heavy duty vehicles such as buses or lorries [19]. The only similarity between them is they are both under U.S. cycle program [11].

4.5 REP05 drive cycle

Representative Non-LA4 cycle or REP05 cycle was derived by EPA alongside two other drive cycles which are SC03 drive cycle and the Remnant (REM01) drive cycle [20]. The driving data were collected before the year 1995, prior to the repeal for the federal freeway speed limit to be 55 mph or 88.51 km/h [21]. The data were taken in Baltimore, Spokane, and Atlanta. Then, they were used in developing these three drive cycles. Baltimore was selected as it represented a medium sized, northeast area that does not attain the ozone [21]. On the other hand, Spokane was chosen because it is a standard carbon monoxide non-attainment area and a fitting mid-west city could not be located [21].

The three drive cycles did a wonderful job in describing the driving pattern in urban area. REP05 drive cycle represents aggressive driving pattern reflected by the higher average speed and higher acceleration [20]. It also describes the effects of the micro transient that the current UDDS did not cover while the driving pattern that is not represented by this REP05 cycle is covered by the REM01 cycle [20], [22]. However, REP05 test usually does not performed in the process of certification as it would introduce an additional cost for testing. Hence, it is not practical to use this drive cycle for projecting on road fuel economy.

REP05 drive cycle is for light-duty vehicle testing only [21]. By looking at Figure 8, the range of speed for REP05 drive cycle is 0 – 129.33 km/h and the average speed is 82.88 km/h.

This test cannot be done on a traditional chassis dynamometer with 0.22 m twin rolls as it will cause the tires to slip due to the high-speed profile. Thus, a 1.22 m single roll chassis dynamometer is used [23]. As a matter of fact, the ARB02 drive cycle has higher aggressive acceleration occurrences than the REP05 cycle and the aggregation of them to a certain extent is utilized to produce the US06 drive cycle [20], [22]. Evaluating the in-use emissions is the main function of this cycle [22].

4.6 HWFET drive cycle

Another drive cycle developed by EPA under the U.S. cycles program is the Highway Fuel Economy Test (HWFET) cycle [11]. This drive cycle is specified for light duty vehicles like cars [11]. As the name is, it represents the driving pattern at highways. HWFET driving cycle is one of the four standard drive cycles used in the determination of the average fuel economy for cars and also light trucks. The other three drive cycles are the US06 cycle, the Federal Test Procedure (FTP), and one of the Supplemental Federal Test Procedure (SFTP) – the SC03 drive cycle [13]. HWFET drive cycle is mainly for determining the rating of fuel economy on highway area [24].

This drive cycle is a hot-start test with a warmed engine. The trips that are included in this drive cycle is a long trip without any sort of traffic jams. A combination of rural and interstate highway driving is represented by the drive cycle [25].

Moreover, this cycle is among the standard driving cycles used to compare the proposed vehicle simulator with ADVISOR [13]. As what we can observe from Figure 9, HWFET driving cycle does not have any stops beside in the beginning and the end as it is after all, a driving pattern on a highway. Hence, the number of stop phases for HWFET drive cycle is less than other drive cycles [24]. 77.57 km/h is the average speed of the cycle and the speed ranges from 0 to 96.4 km/h. It will produce the U.S. Corporate Average Fuel Economy (CAFÉ) standards when combined with FTP-75 drive cycle [24]. CAFE is used to obtain the total emission of carbon dioxide in the case of driving both in the city and highway. The formulated equation is as follows:

$$CO_{2(CAFÉ)} = 0.55 \times CO_{2(FTP-75)} + 0.45 \times CO_{2(HWET)} \qquad (1)$$

4.7 US06 drive cycle

We mentioned earlier in subsection 4.5 that the "aggregation" of the ARB02 drive cycle developed by California Air Research Board (CARB) and REP05 drive cycle formulated by Environmental Protection Agency (EPA) to some extent will produce US06 drive cycle [22]. Note that both of the drive cycles aggregated are having high speed and high acceleration thus, the US06 drive cycle also consists of high acceleration level to represent aggressive driving behavior and transient operations [20]. The main purpose of this drive cycle is to cover the high speed and acceleration that is not covered by the FTP-75 drive cycle and that is why it is called the Supplemental Federal Test Procedure (SFTP) [1], [11].

This cycle belongs to the U.S. cycles program and is being used by the EPA to provide a control over the emission of non-UDDS driving pattern [11], [20]. It is one of the standard driving cycles in comparing the dynamic vehicle simulator with ADVISOR [13]. Moreover, it is derived after 2008 based on the actual in-use driving segments. US06 is another cycle classified under highways or main roads for the category of area covered [1].

We also mentioned in subsection 4.6 that US06 drive cycle is the standard drive cycle that is being used to determine the fuel economy of light duty vehicles together with three other drive cycles which are HWFET driving cycle, Federal Test Procedure cycle (FTP), and SC03 cycle [13]. Although it serves its purpose, some things need to be considered before running the test as some light duty vehicles may not be able to cope with the high speed and acceleration of US06 drive cycle [20]. From Figure 10, the speed range is from 0 to 129.23 km/h which is very high, and the average speed is 77.2 km/h.

Even though US06 cycle is clearly more aggressive than FTP cycle, its fuel economy (miles per gallon) is actually higher than the FTP's bag 2 (hot-transient phase as being mentioned in subsection 4.4). The emissions of US06 cycle is lower than the emissions of FTP's bag 2 [20]. The average temperature and the maximum temperature for a vehicle's catalyst are higher after being tested over the US06 drive cycle compare to the FTP drive cycle [20]. It is also important to note that a single roll dynamometer with a large diameter or something similar is required for the US06 test [20].

4.8 SC03 drive cycle

This drive cycle under the U.S. cycles program represents the driving pattern for urban area [1], [11]. It contains many stops in contrast with the HWFET driving cycle and from Figure 11, we can see that the average speed is just 34.5 km/h while the speed range varies from 0 to 88.19 km/h. This is pretty much relatable to urban area driving. This driving cycle is also a Supplemental Federal Test Procedure (SFTP) alongside US06 drive cycle [11].

It is used to determine the load of engine and the associated emissions with the air conditioning running throughout the trips under hot surrounding temperature which is 95°F or 35° C [11], [25]. Fundamentally, the SC03 drive cycle is derived from the FTP-75 drive cycle integrated with the usage of air conditioning while driving. The windows of the vehicle are closed during the test. The fan setting is set to the highest and the air conditioning is set to maximum with the lowest temperature setting.

SC03 is a standard driving cycle applied to make a comparison between the dynamic vehicle simulator and the ADVISOR [13]. This particular drive cycle is also one of the four standard driving cycles utilized in determining average fuel economy estimation for cars and light trucks. Those four driving cycles are [13]:

1) Federal Test Procedure (FTP) drive cycle
2) Highway Fuel Economy Test (HWFET) drive cycle
3) US06 drive cycle
4) SC03 drive cycle

4.9 BUSTRE drive cycle

Other than that, BUSTRE drive cycle was developed and measured by Keith Wipke from National Renewable Energy Laboratory (NREL) [26] on 12 Jun 1998. This drive cycle was investigated on a 16th Street Mall bus in Denver, Colorado, US. This electric-powered bus as shown in Figure 21, will undergo experiment which will travel around 1.65-mile round trip, with the bus stopping at every block and bus stop. Based on Figure 12, the bus would reach the highest speed of about 18 mph somewhere between 28 peaks which indicate the bus has arrive at start and stop center. The bus accelerates and decelerates continuously from one stop center to another stop center.

This purpose of this driving cycle is basically to determine the average time travelled taken by the bus to travel at between stop center which will improve the efficiency or effectiveness of service provided where next may represent the rate of traffic at certain side of city. Other than that, the drive cycle is used to measure the electric consumption for each bus to complete their every trip around 1.65 miles. The lower the bus in used may indicate downtime for maintenance or purposeful reduction of planned work for the buses.

Figure 21: Electric bus stopped in one of the stations

4.10 ARB02 drive cycle

As mentioned in subsections 4.5 and 4.7, this driving cycle also was developed by the California Air Resources Board (CARB) based on data from their Los Angeles chase car study. The objectives of ARB02 cycle is to test the vehicles which was over in-use operation outside of the FTP that also including extreme in-use driving events [7].

From Figure 13, this drive cycle is specialized to shows the vigorous movement of vehicle, means that the vehicle undergoes high acceleration and high deceleration. The highest speed achieved by the car is around 80.3mph which very high for a very short time, while the average speed for whole trip is 43.5mph [11]. This kind of speed models is important as in some research of DC machines, the rate of speed will indicate the ratio of operation whether the DC machines will act as generator or motor since it obeyed the respective properties. Thus, the efficiency of energy consumption is also dependent on having a large weight of vehicles which are accelerating or decelerating [27].

4.11 CLEVELAND drive cycle

This drive cycle was developed by Ohio State University Formula Electric Team on 22 March 2001. The driving cycle was tested on a formula electric car in racing competition at Cleveland Burke Lakefront Airport in 1997. This university had won the race competition.

From Figure 14, it shown that the formula car was at warm-up session for the first 200 seconds. During this warm-up session, this electric racing car had achieved the highest speed around 49.87mph and then decrease about 32.5mph before it starts to accelerate up to the highest top speed of 100.43mph which are very high. We can see that, there are 4 of total similar peaks was formed by a range of 43.0mph until about 100.0 mph. These peaks are indicating the total laps taken by the racing car. The average speed of the session is 57.9mph [11]. This prove that the electrical power is more than enough to powered-up the vehicle to achieve high torque speed.

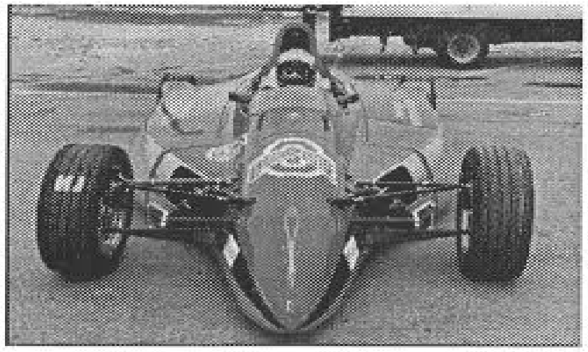


Figure 22: Electric car race

Figure 23: Experiment using chassis dynamometer conducted in laboratory

4.12 Japanese 10-15 drive cycle

The 10-15 mode cycle was developed in Japan as it used to test the emissions and fuel consumption for light duty vehicles. Over the period of 2008-2011, this cycle was gradually replaced by a newer driving cycle called as JC08 cycle. The 10-15 mode test is extracted from 10 mode cycle by combining by another 15-mode segment of a maximum speed of 70km/h [11]. The emission was measured and expressed in g/km.

However, for ANL Prius Test the concept of 10-15 mode cycle is applied to get the data. Prius is one of Toyota model of PHEV. It was measured by chassis dynamometer as shown in Figure 23. The entire cycle consists of a sequence of fifteen minutes warm-up at 37.28mph, idle test, and then five minutes warm-up at 37.28mph and one 15-mode segment. After that, it was followed by three repetitions of 10-mode parts and one 15-mode part. Refer Figure 15. The range of speed varies between 0 mph - 43.96 mph and the average speed is 14.2 mph.

4.13 ECE, EUDC, and NEDC drive cycle

These three drive cycles were developed in Europe. ECE + EUDC test cycle, or also known as MVEG-A cycle had been used for EU type approval testing of emissions and energy consumption for light duty vehicles. This test is performed by a chassis dynamometer. This cycle which is very similar to MVEG-B which next is called as NEDC shown in Figure 19 is basically consist of four ECE segment, Figure 16 and followed by one EUDC segment, Figure 17. Before experiment the cycle, the vehicle was allowed to soak for at least 6 hours at a test temperature of 20-30°C. Then, it can start to idle for 40s.

The test starts with four repetitions of the ECE cycle. This cycle is an urban driving cycle, that also known as UDC. It was developed to represent city traffic or driving condition such as at Paris or Rome. This cycle is characterized by low exhaust gas temperature, low vehicle speed, and low engine load.

The Extra Urban Driving Cycle or EUDC segment has been added by right the fourth UDC cycle to take for more aggressive, and high-speed driving modes. This drive cycle can achieve the maximum speed of EUDC cycle for about 120km/h. An EUDC cycle for low-powered vehicles has also been constructed with a maximum speed only limited to 55.98mph, Figure 17 [28].

The emissions from the vehicles are then sampled according to the constant volume sampling (CVS) method. It was analyzed and expressed in g/km for each of the emissions. The following Table 7 includes a summary of selected parameters for the construction of ECE, EUDC and NEDC cycles.

Table 7: Parameter that shows the relationship between the drive cycle

Characteristics	**Unit**	**ECE15**	**EUDC**	**NEDC** [+]
Distance	km	0.9941	6.9549	10.9314
Total time	s	195	400	1180
Idle (standing) time	s	57	39	267
Average speed (incl. stops)	km/h	18.35	62.59	33.35
Average driving speed (excl. stops)	km/h	25.93	69.36	43.10
Maximum speed	km/h	50	120	120
Average acceleration [1]	m/s^2	0.599	0.354	0.506
Maximum acceleration [1]	m/s^2	1.042	0.833	1.042

[+] Four repetitions of ECE 15 followed by one EUDC

[1] Calculated using central difference method

5.0 CONCLUSION

This study aims to compare the difference of many types of drive cycles which have been developed around the world whether it is legislative or non-legislative. Different drive cycles have different purpose which can represent the topography of specific research area and also energy consumption by the vehicle such as light duty vehicle, truck, bas, and racing car. They are INRETS, Indian DC, Manhattan, UDDC, REP05, HWFET, US06, SC03, BUSTRE, ARB02, CLEVELAND, Japanese 10-15 mode, ECE, EUDC, and NEDC. The drive cycles are basically created as it can help researcher to determine a new technology in electrical automotive field as the world nowadays moving toward zero carbon emissions. Thus, the deep learning on how driving cycle works to estimate the energy consumption within a specific area would be very important.

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