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# A methodology to creating semi-artificial city driving cycle: case study of Istanbul

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## Abstract

This study describes the methodology of creating Semi - Artificial City Cycle (SACC), which can be used for emission tests of road vehicles; sustainability of hybrid electric vehicle (HEV); or emission inventories of the city. This methodology uses the half-hour frequency traffic data of Istanbul to calculate the average speeds and travel distances of urban, rural and highway segments. Then, calculated average data convert into instantaneous time—velocity distribution by random time—speed values, which are appropriate for acceleration/deceleration of real-world driving. In addition, in this study, the obtained artificial cycles and the regulation cycle are modelled in the AVL Cruise software to compare, and the driving dynamics of the city are examined. The SACC has different acceleration/deceleration distribution, average driving speeds, trips and travel times than regulation tests. However, according to the simulation results, the same fuel consumption and CO<sub>2</sub> emission factors are obtained with the regulation test, except for the highway segment.

**Keywords:** Average traffic data, Artificial driving cycle, Modelling CO<sub>2</sub> emission

## Introduction

### Literature Review

The driving cycles for road vehicles are used primarily to test emissions, to determine fuel consumption and performance values and to create emission inventories. In addition, the driving cycles are used to investigate the battery endurance, electricity and power consumption of hybrid or electric vehicles [1–4]. For this reason, it is desired that a driving cycle should reflect the real traffic conditions.

Due to emission standards of road vehicles were not suitable for real driving conditions, researchers have worked to create city cycles and reveal the driving dynamics for decades. One of these studies is the Istanbul Driving Cycle (IDC), which was made in 1997 based on the thesis claiming that EURO standard test cycle does not reflect real traffic conditions [5, (Sorousbay: Çevre Deklerasyonu Ek VIII; Binek Taşıtların Ülkeye Özgün Yakıt Tüketimlerinin ve Emisyon Faktörlerinin Belirlenmesi, unpublished)]. In tests done with 30 vehicles, it has been revealed that the New European Driving Cycle (NEDC) does not reflect real traffic conditions, and IDC is different from both NEDC and FTP-75 American cycle. Since 1997, similar studies have been carried out in the

world [6–15], and they have been concluded that different countries and even cities have different driving dynamics such as stop duration, acceleration/deceleration pattern, mean cruise speed and maximum speed. Because of all these studies, the new EURO standard Worldwide Harmonized Light-Duty Test Procedure (WLTP) has become a better reflective test procedure for real driving emission [16–18].

This new test procedure has made it mandatory to carry out tests in real traffic conditions in addition to laboratory tests [19]. According to this procedure, fuel consumption and CO<sub>2</sub> emission factors are mainly determined by laboratory tests, while other pollutant emissions are mainly determined by real driving emission (RDE) tests [20]. Even if the RDE route is not determined, it has been shaped with many boundary conditions such as segment-based average speed, altitude change and air temperature [21]. Although the WLTP came into force in the European Union in 2018 (and in some other countries like Japan, China and Turkey), the old test procedures are still used in the rest of the world [22].

Despite renewed regulations, creating city driving cycles that represent real traffic conditions is a popular research topic even today. Many scientists have obtained cycles that reflect real traffic conditions by following different methodologies [23–25]. The most common of these methodologies is to create an acceleration distribution matrix with respect to the average velocity (or named in literature, speed acceleration frequency distribution (SAFD)). Thanks to this matrix, the driving dynamics of the traffic are extracted, and cycles that better reflect the real driving conditions can be obtained [5, 15, 26, 27].

Although segment separation of driving cycles is not observed in most studies, it is another method to create segmented driving cycles. For instance, in a study that performs data analysis using the SAFD matrix, segment-based driving cycles were created [28]. Although segment-based driving cycle is created in our study, we use a quadratic polynomial expressing the acceleration-average velocity distribution instead of the SAFD matrix and form artificial speed values that comply with the acceleration/deceleration pattern. Another feature of this study is to minimize the workload by creating an artificial cycle based on the average traffic data. The artificial cycle generation method [29, 30], which is also available in the literature, is an accepted method in terms of analysing the emission factors and fuel consumption of vehicles.

### **Aim and Scope of the Study**

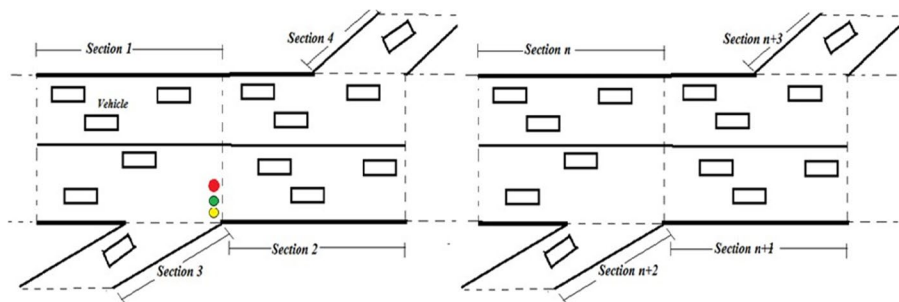
As understood from the literature review, driving cycles are needed to determine the fuel/energy consumption or exhaust emissions of light-duty and passenger vehicles. However, creating a driving cycle requires good statistical data analysis, high cost and time. The aim of our study is to create a semi-artificial driving cycle by analysing the road traffic data with a different perspective via saving time and cost at the same time. To do this, time mean speed (TMS) values are calculated for each time zone of the day on different road segments (urban, rural and highway), and artificial cycles suitable for TMS are created. Although these created cycles have artificial speed values, they reflect the driving behaviour of the city as stopping times/durations, acceleration/deceleration patterns and average speeds. While in the traditional methods, lots of tests must be performed on different routes of the city to obtain the speed distribution, it is easier to get a cycle by using existing traffic flow data thanks to this method.

### Methods

The aim of the study, unlike the driving cycle derivation methods available in the literature, is to generate random cycles that contain real traffic conditions. Although these cycles contain artificial speed data, they are well-founded due to including real driving dynamics and reflecting average traffic activity. The average traffic activity gathered by more than one hundred thousand vehicles, which deliver data every 5 s in every day of the week. A representative image describing the collection of the traffic activity data is given in Fig. 1.

The small road sections shown in Fig. 1 are obtained with the nodal points used in the mapping. The  $n$  given in the figure represents the total number of road section. In the urban and rural road segments, traffic lights, pedestrian crossings, traffic signs, intersections and junction points are used to define nodal points, while in the highway segment, traffic signs, junction point and highway toll booths are used. Each vehicle (with equipment) passing through these road sections collects speed and position information at frequencies of 5 s. Although these collected data give very good results in terms of understanding the traffic density, they contain some uncertainties. For example, the data filtered according to half-hour intervals cause the misunderstanding of vehicle number due to the much more signal number coming from the same car. With a clear expression, if  $y$  number of vehicles stay at least 10 s on the same road segment, they give two or more signals and cause the miscalculation of the vehicle number. This can occur in low-speed situations or on long road segments. On the other hand, no data is gotten while high-speed driving on enough short road segments. This affects the accuracy of the calculation of the average vehicle number. However, these data are ideal for determining average traffic speeds or average trips. The presentation of the filtered data is given in Table 1.

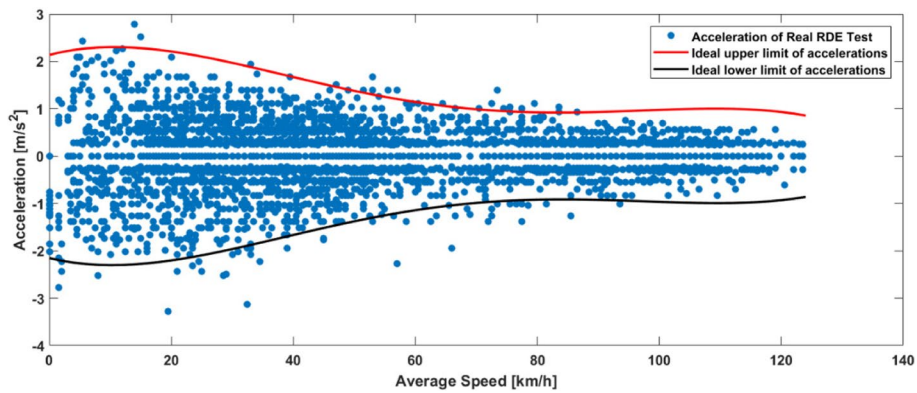
A symbolic presentation of filtered data with half-hour time periods is given in Table 1. Here,  $N_{i,(j-1)*30}$  and  $V_{i,(j-1)*30}$  are the number of vehicle and half-hour average speed in segment  $i$  (from 1 to  $n + 3$ ) at time  $(j-1)*30$  ( $j$  is from 1 to 48). If all segments are classified with respect to the regulated speed limit, urban, rural and highway road parts could be obtained. Then, classified traffic activity data could be used to get the average driving pattern



**Fig. 1** An example of road traffic data and road segments

**Table 1** An example of half-hour-based traffic activity data

Sections	0:00–0:30		0:30–01:00		...		23:30–0:00	
	<i>N</i>	<i>V<sub>mean</sub></i>	<i>N</i>	<i>V<sub>mean</sub></i>	<i>N</i>	<i>V<sub>mean</sub></i>	<i>N</i>	<i>V<sub>mean</sub></i>
Section 1	<i>N</i> <sub>1,0</sub>	<i>V</i> <sub>1,0</sub>	<i>N</i> <sub>1,30</sub>	<i>V</i> <sub>1,30</sub>	...	...	<i>N</i> <sub>1,1410</sub>	<i>V</i> <sub>1,1410</sub>
Section 2	<i>N</i> <sub>2,0</sub>	<i>V</i> <sub>2,0</sub>	<i>N</i> <sub>2,30</sub>	<i>V</i> <sub>2,30</sub>	...	...	<i>N</i> <sub>2,1410</sub>	<i>V</i> <sub>2,1410</sub>
Section 3	<i>N</i> <sub>3,0</sub>	<i>V</i> <sub>3,0</sub>	<i>N</i> <sub>3,30</sub>	<i>V</i> <sub>3,30</sub>	...	...	<i>N</i> <sub>3,1410</sub>	<i>V</i> <sub>3,1410</sub>
Section <i>n</i> + 1	<i>N</i> <sub><i>n</i>+1,0</sub>	<i>V</i> <sub><i>n</i>+1,0</sub>	<i>N</i> <sub><i>n</i>+1,30</sub>	<i>V</i> <sub><i>n</i>+1,30</sub>	...	...	<i>N</i> <sub><i>n</i>+1,1410</sub>	<i>V</i> <sub><i>n</i>+1,1410</sub>
Section <i>n</i> + 2	<i>N</i> <sub><i>n</i>+2,0</sub>	<i>V</i> <sub><i>n</i>+2,0</sub>	<i>N</i> <sub><i>n</i>+2,30</sub>	<i>V</i> <sub><i>n</i>+2,30</sub>	...	...	<i>N</i> <sub><i>n</i>+2,1410</sub>	<i>V</i> <sub><i>n</i>+2,1410</sub>
Section <i>n</i> + 3	<i>N</i> <sub><i>n</i>+3,0</sub>	<i>V</i> <sub><i>n</i>+3,0</sub>	<i>N</i> <sub><i>n</i>+3,30</sub>	<i>V</i> <sub><i>n</i>+3,30</sub>	...	...	<i>N</i> <sub><i>n</i>+3,1410</sub>	<i>V</i> <sub><i>n</i>+3,1410</sub>



**Fig. 2** Acceleration—speed distribution obtained in tests done on real traffic conditions

**Real Driving Characteristics**

In order to convert the average speed data to instant values, artificial speed values are created. However, for these speed values to be logical, they must be based on actual driving characteristics. A few real driving tests were carried out on random routes with a light-duty vehicle equipped with OBD and GPS hardware to get real driving characteristics. Then, the distribution of acceleration/deceleration values according to instantaneous speed was obtained. Values such as instantaneous speed, engine speed and engine load were collected with the OBD hardware installed on the vehicle, while instantaneous speed and location data were collected with GPS. The acceleration/deceleration versus average velocity distribution, which is collected with a few real driving tests, is given in Fig. 2.

If the distribution given in Fig. 2 is examined, it is seen that the acceleration/deceleration limits can be expressed with parabolic equations according to the average speed. So, in this study, parabolic equations are used to model driving dynamics instead of the SAFD matrix. The acceleration upper limit and deceleration lower limit can be calculated as given in Eqs. 2.1 and 2.2.

$$a_{up} = -8.618e - 08 * V^4 + 2.337e - 05 * V^3 - 1.926e - 03 * V^2 + 3.347e - 02 * V + 2.136 \tag{2.1}$$

$$a_{low} = 8.254e - 08 * V^4 - 2.245e - 05 * V^3 + 1.850e - 03 * V^2 - 3.116e - 02 * V - 2.155 \tag{2.2}$$

$a_{up}$  and  $a_{low}$  are the acceleration/deceleration upper and lower limits, and  $V$  is the mean velocity. 97.5% of the real acceleration/deceleration distribution given in Fig. 2 stays between  $a_{up}$  and  $a_{low}$  curves. Therefore, using these curves while controlling the acceleration/deceleration of artificial velocity values causes an error of 2.5%.

### Artificial Istanbul Driving Cycle

With the changed emission regulation, a new driving cycle, Worldwide Harmonized Light-Duty Cycle (WLTC), which is accepted by European countries and some other developed countries, comes into force. Although this cycle is more realistic and more dynamic than NEDC, creating a city cycle is still a topic of current research, since it is an unchangeable fact that every city has its own driving dynamics [11–13]. For this reason, real driving emission tests are also required in the new emission regulation along with WLTC tests. Although these real driving tests will be carried out in random traffic conditions, they should be carried out on routes that meet certain boundary conditions specified in the EU regulation [21]. In this case, the question arises: do the RDE routes reflect the average driving behaviour of cities? For this reason, in this study, it is thought that a city cycle might still be needed, and it is studied how a new cycle could be created for Istanbul.

The methodology to create the new Istanbul Driving Cycle is different from literature studies. This methodology involves artificial speed, which depends on real average traffic data and real acceleration/deceleration patterns. It also considers average hourly travel distances instead of a fixed travel distance. According to this method, hourly trip length of road segments could be achieved like Eq. 2.3.

$$\text{Trip}_{i,t} = \frac{\sum N_{i,j,t} L_{i,j,t}}{\sum N_{i,t}} * W_{i,t} \quad (2.3)$$

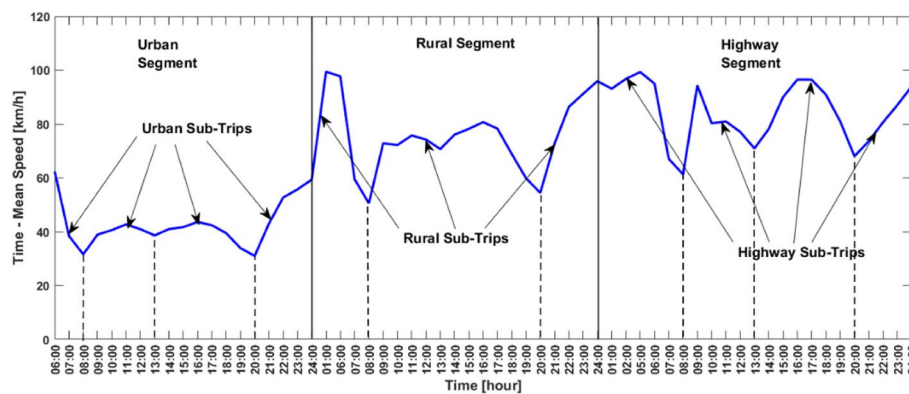
$\text{Trip}_{i,t}$  is the hourly average trip length of segment  $i$  ( $i$ : urban, rural and highway),  $N_{i,j,t}$  and  $L_{i,j,t}$  are vehicle number and road length in segment  $i$  and section  $j$  at time  $t$ , respectively.  $N_{i,t}$  is the total number of data vehicle (DV) which give traffic data in segment  $i$  at time  $t$ , and  $W_{i,t}$  is the weight factor in segment  $i$  at time  $t$  to define the dependence on traffic density and it is between 0 and 1. The weight factor ( $W_t$ ) is the ratio of the total number of DV in the time period of  $t$  to the total number of DV in peak traffic hour, and it is given in Eq. 2.4.

$$W_{i,t} = \frac{N_{i,t}}{\max(N_{i,t})} \quad (2.4)$$

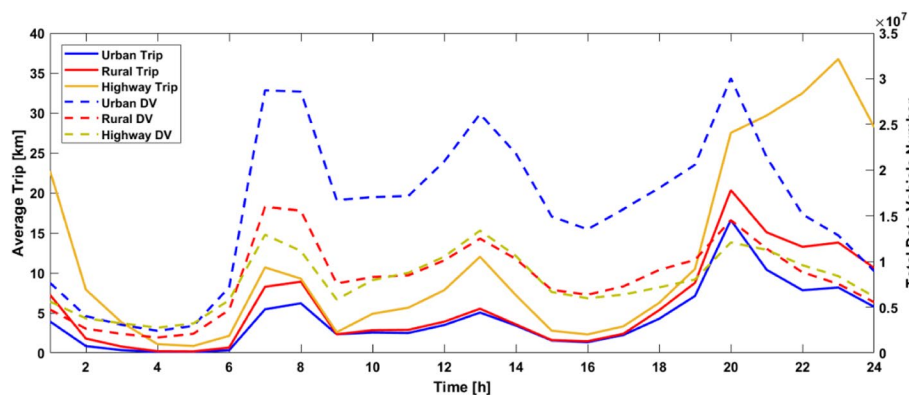
The  $\max(N_{i,t})$  given in the Eq. 2.4 is the maximum DV number in segment  $i$  for the whole day. The hourly average speed of each segment could be calculated as in Eq. 2.5.

$$V_{i,t} = \frac{\sum V_{i,j,t} N_{i,j,t}}{\sum N_{i,j,t}} \quad (2.5)$$

$V_{i,t}$  is the hourly time mean speed (TMS) of segment  $i$  at time period of  $t$ . In fact, this is the weighted average speed, since we calculate it as a ratio of the sum of the total speed



**Fig. 3** Time—the mean speed of Istanbul traffic



**Fig. 4** Distribution of average trip and DV number per hour according to Istanbul road segments

(average speed of section  $j$  multiplied by the vehicle number of section  $j$ ) to the sum of the vehicle number. The graphic of TMS of road segments is given in Fig. 3.

As seen in Fig. 3, TMS of Istanbul city is given based on road segments. The  $x$ -axis represents the hour of a day for all road segments separately. Every segment is separated into macro trips (sub-trips) according to local minimum points, which are rush hours. It can be said that rush hour shows the same effect on traffic for all segments.

In Fig. 4, hourly average trip lengths and DV numbers of urban, rural and highway are given. As seen in the figure, the travel distance per vehicle in urban and rural road segments is approximately the same at most times of the day. On the other hand, the travel distance per vehicle in the highway segment at any time of the day is higher than in other segments. The average trip length is the lowest in the early morning (between 4 and 6) due to the low number of vehicles and short-distance travels. Since there are business entrance hours between 6 and 8, the number of vehicles (DV) has increased, but travel distances have remained short. In the middle of the day, the DV increases and travel distances increase compared to the previous hours. Since there is a rush hour after 5 pm, the number of vehicles and travel distances increase until 8 pm and then decrease. The daily average trips of urban, rural and highway segments are 5.5 km, 6.2 km and 11.5 km, respectively.



Although these findings show the average traffic pattern of the city, they are not sufficient to establish a driving cycle. To create a cycle, we need instant velocity instead of mean speed. However, instantaneous speed changes are not available since GPS tests were not conducted for the whole city. Therefore, artificial speed values providing hourly average driving velocities are created with the MATLAB software. These artificial speed values are controlled by acceleration/deceleration limits, which are get by real driving tests, to make them more meaningful. The steps of the methodology described up to this part are calculated as given in Eqs. 2.6, 2.7, 2.8, 2.9, 2.10, 2.11 and 2.12.

$$V_{k,i,t} = \text{Random}(0, 140) \text{ [km/h]} \tag{2.6}$$

$$a_{k,i,t} = \frac{V_{k,i,t} - V_{k-1,i,t}}{3.6 * (t_{k,i,t} - t_{k-1,i,t})} \text{ [m/s}^2\text{]} \tag{2.7}$$

$$\text{if } a_{\text{low}} \leq a_{k,i,t} \leq a_{\text{up}} \text{ continue; else go to Eq.2.6} \tag{2.8}$$

$$d_{k,i,t} = \left( \frac{\text{mean}(V_{k-1,i,t}, V_{k,i,t})}{3.6} * (t_{k,i,t} - t_{k-1,i,t}) \right) / 1000 \text{ [km]} \tag{2.9}$$

$$d_{i,t}^{\text{new}} = \frac{d_{i,t}}{\sum_{t=1}^{t=24} d_{i,t}} * \text{mean}(d_i) \tag{2.10}$$

$$\text{if } \sum_{n=2,i,t}^{n=k,i,t} d_n \geq d_{i,t}^{\text{new}}; V_{k_{\text{mean}},i,t} = \frac{3600 * \sum_{n=2,i,t}^{n=k,i,t} d_n}{t_{k,i,t} - t_{2,i,t}} \text{ [km/h]} \tag{2.11}$$

$$\begin{aligned} &\text{if } V_{i,t} * 0.95 \leq V_{k_{\text{mean}},i,t} \leq V_{i,t} * 1.05 \\ &V_{\text{cycle}} = [V_{\text{cycle}}; V_{k,i,t}] \text{ else go to Eq.2.6} \end{aligned} \tag{2.12}$$

The  $k$ ,  $i$  and  $t$  indices given in the equations are used for the “ $k$ th” random value (for velocity, acceleration/deceleration or distance) at “ $t$ ” time in “ $i$ ” segment.  $V_{k,i,t}$  is uniformly distributed pseudorandom value selected between 0 and 140 km/h and represents the velocity at time  $t$  in segment  $i$ ,  $a_{k,i,t}$  is the acceleration or deceleration and  $d_{k,i,t}$  is the distance change per second at time  $t$  in segment  $i$ . After checking the acceleration/deceleration value in Eq. 2.8, the travelled distance per second is calculated in Eq. 2.9. In Eq. 2.10,  $d_{i,t}$  represents the trip length at time  $t$  in segment  $i$ ; by multiplying the rate of the specific trip by the total trip  $\left(\frac{d_{i,t}}{\sum_{t=1}^{t=24} d_{i,t}}\right)$  with the average daily trip (mean ( $d_i$ )), we calculate the normalized trip length ( $d_{i,t}^{\text{new}}$ ) at time  $t$  in segment  $i$ . If the sum of  $d_{k,i,t}$  ( $\sum_{n=2,i,t}^{n=k,i,t} d_n$ ) is equal to or higher than the  $d_{i,t}^{\text{new}}$ , the average of selected random velocity values ( $V_{k_{\text{mean}},i,t}$ ) is calculated as in Eq. 2.11. After the calculated average, velocity ( $V_{k_{\text{mean}},i,t}$ ) is compared with the real mean speed of segment  $i$  at time  $t$  ( $V_{i,t}$ ) with a tolerance of 5%; the artificial driving cycle is created gradually. Five different Artificial Istanbul Driving Cycles (AIDCs) obtained via this methodology and average speed of Istanbul traffic are given in Fig. 5.

In Fig. 5, the black lines represent the real average speed obtained with hourly-filtered traffic activity data, and the other lines represent the AIDC (C1 is cycle 1, C2 is cycle 2, etc.) which is gained with the methodology mentioned above. To represent starting, finishing and idling conditions, zero speeds are added to the beginning and end of road segments (urban, rural and highway). In this step, attention is paid to ensure that the total stopping times are approximately the same rate as WLTC for class 3b. The characteristic features of AIDCs and WLTC are given in Table 2.

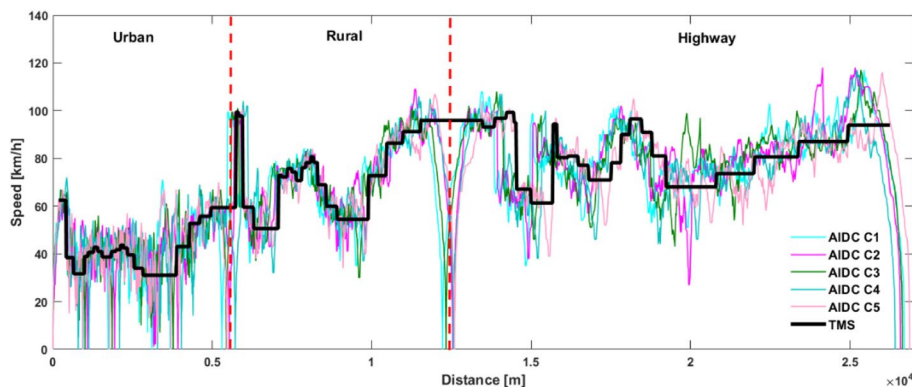
Low and medium segments of WLTC [31] are called urban, high segment of WLTC [31] is called rural and extra high segment of WLTC [31] is called highway in this study. For AIDCs, urban, rural and highway segments are determined according to the regular speed limits. As can be seen in Table 2, the average speeds of the AIDCs and WLTC in the urban and rural segments are more close to each other contrary to the highway segment, but the travel distances are different. Compared to the highway segment, the average speed of WLTC is higher, but the travel distance is lower than that of AIDCs. As a result, artificial cycles have a higher average speed

## Results and Discussion

Since the European Commission updated its emission regulations in 2017 [32], it is thought that polluting gases are measured more realistically thanks to the more dynamic WLTC laboratory cycle and additional Real Driving Emission (RDE) tests [33]. However, it is a research subject whether the boundary conditions specified in the regulation and the real traffic conditions match. For this reason, in our study, the average driving behaviour of Istanbul, one of the largest metropolises in the world, is determined by using real traffic flow data. These average values are analysed in the computer environment to obtain a testable driving cycle. With the engine fuel consumption map based on real driving emission tests, simulations are made in the AVL Cruise software. Specifications of the vehicle used in the real driving test and computation model are given in Table 3.

Acceleration/deceleration distributions of WLTC and AIDCs are given in Figs. 6 and 7, respectively, and engine operating conditions of all driving cycle is given in Fig. 8.

In Figs. 6 and 7, acceleration/deceleration distributions according to the average vehicle speed and engine working conditions of WLTC and AIDCs modelled in the AVL Cruise software are given. The bold area given in Figs. 6 and 7 represents



**Fig. 5** Average speed values of Istanbul traffic and artificial cycles

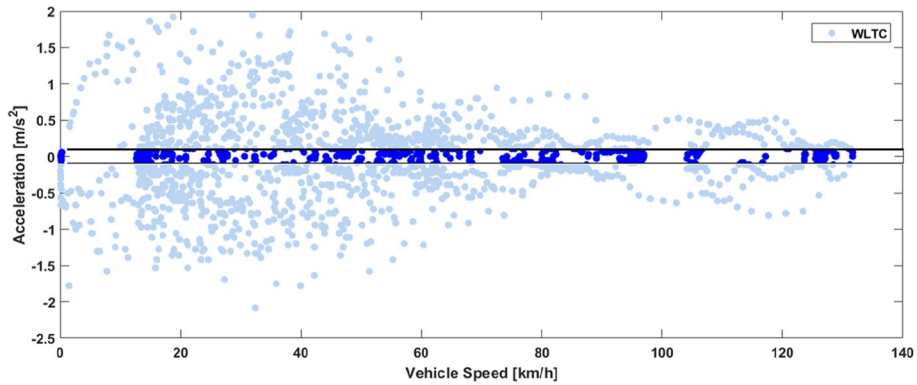


**Table 2** General features of WLTC and AIDCs

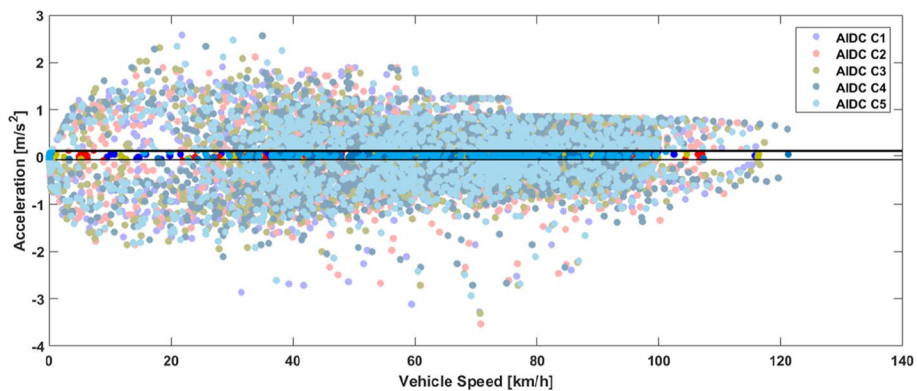
Driving cycle	Urban			Rural			Highway			Average speed while idling [km/h]
	Time [s]	Distance [km]	Average Speed [km/h]	Time [s]	Distance [km]	Average Speed [km/h]	Time [s]	Distance [km]	Average speed [km/h]	
WLTC	1022	7.85	27.7	455	7.16	56.7	323	8.25	92	46.5
AIDC1	580	5.3	32.9	417	6.92	59.7	755	14.48	69	54.1
AIDC2	605	5.53	32.9	408	7.01	61.8	749	14.04	67.5	53.8
AIDC3	610	5.44	32.1	395	6.88	62.7	740	14.32	69.7	55.1
AIDC4	632	5.72	32.6	404	6.84	60.9	716	13.86	69.7	54.9
AIDC5	607	5.45	32.3	424	7.14	60.6	749	14.27	68.6	54.4

**Table 3** Specifications of the test vehicle

Vehicle specifications	Engine specifications
Five speed manual light-duty	1.6 L four-cylinder diesel engine
Weight: 1450 kg and odometer: 93,000 km	Max. power: 92 hp @ 4000 rpm and max. torque : 230 Nm @ 2250 rpm
Gear ratios: 1st: 4.85/2nd:2.7/3rd: 1.7/4th: 1.2/5th: 0.92	Common rail, turbocharger

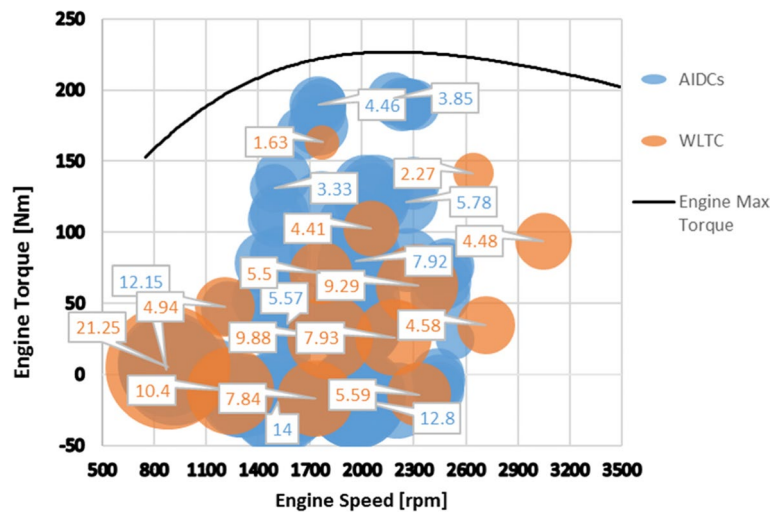


**Fig. 6** WLTC acceleration/deceleration distribution

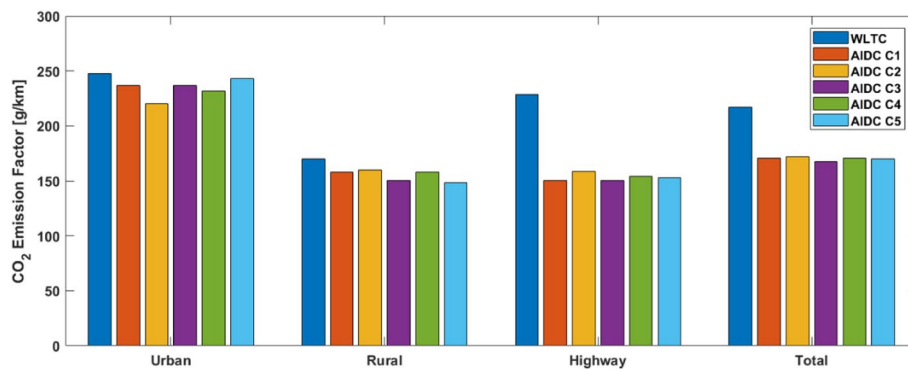


**Fig. 7** AIDC acceleration/deceleration distribution

the region between the  $\pm 0.1$  limits of acceleration/deceleration and is considered as cruise speed. In Figs. 6 and 7, it is clear that the acceleration/deceleration distributions differ for WLTC and AIDCs. The intensity of cruise driving in WLTC and AIDCs is very low below 15 km/h and 25 km/h, respectively. In addition, the acceleration/deceleration distribution in WLTC above 60 km/h is in a narrower range than AIDCs. In Fig. 8, the distributions of the engine operating points obtained as a result of the simulation are given. As can be seen, the engine operating points are formed between 2800 rpm and 3200 rpm due to the high speeds in the extra high phase of WLTC. However, in AIDCs with a maximum speed of less than 120 km/h, engine-working points do not occur in high-speed regions. On the other hand, in AIDCs



**Fig. 8** Engine operating conditions at AIDCs and WLTC cycles

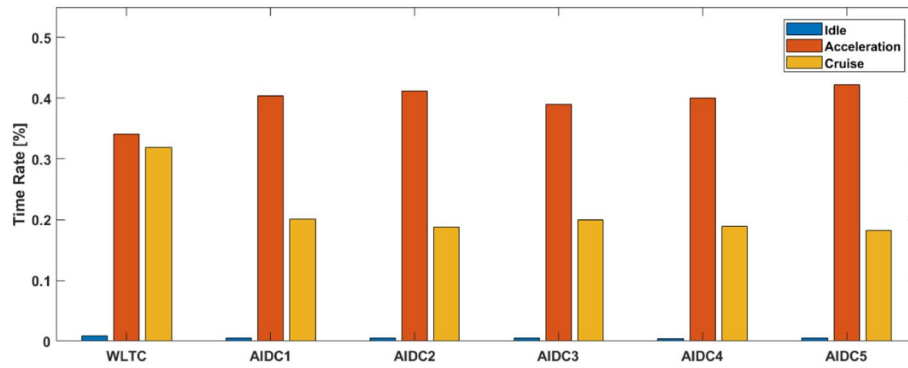


**Fig. 9** Variation of CO<sub>2</sub> emission factors by segments and cycles

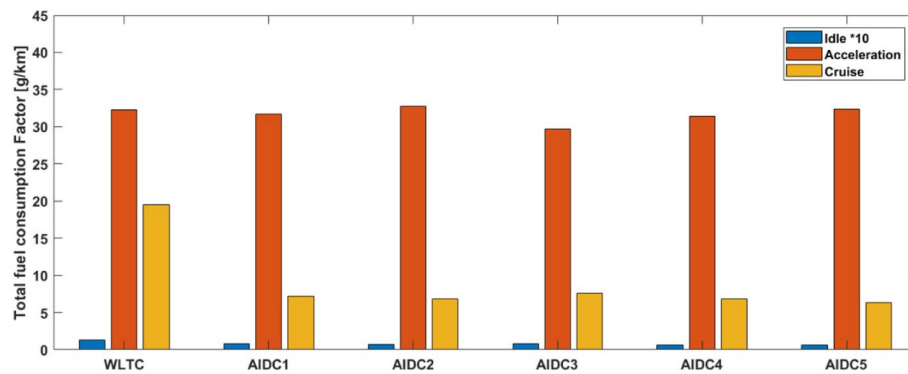
with a wide acceleration range, the engine operated in the full load zone, while in WLTC, the engine remained in the medium load zone.

In Fig. 9, the CO<sub>2</sub> emission factors of the different road segments and the total cycle are given. It is well known that the average speed and CO<sub>2</sub> emission factor have a convex polynomial relationship [34, 35]. This means that higher CO<sub>2</sub> emission is released at low and high speeds, but lower CO<sub>2</sub> emission is released at medium speed. Due to the average speeds of AIDCs and WLTC in the urban and rural segments being close to each other, they are approximately the same CO<sub>2</sub> emission factor. However, since WLTC has higher speeds in the highway segment, the CO<sub>2</sub> emission factor is also higher. When it comes to the whole cycle, a higher CO<sub>2</sub> emission factor occurs in WLTC. This is because the cycle average speed is around 55 km/h in AIDCs while it is 46.5 km/h in WLTC.

In Fig. 10, the time percentages of idling (zero vehicle speed), acceleration and cruise driving of WLTC and AIDCs are given. As the speed lower than 1 km/h is accepted idling condition, cruise driving is received if acceleration is equal to zero or between  $\pm 0.1 \text{ m/s}^2$  limit. The acceleration driving is admitted as higher acceleration than  $0.1 \text{ m/s}^2$ . While the



**Fig. 10** Distributions of the idling (zero vehicle speed), acceleration and cruise driving time rates of the cycles



**Fig. 11** Total fuel consumption factors for cycles according to driving modes

time taken for acceleration in WLTC is about the same as the time taken for cruise speed, the time taken for acceleration in AIDCs is about twice the time taken for cruise driving.

In Fig. 11, The total fuel consumption (TFC) factor for different driving behaviours of all test cycles is given. These factors are calculated with the ratio of total consumed fuel in each driving mode to total trip length. As expected, the zero speed (idling) TFC factor is lowest and the acceleration TFC factor is highest in all driving cycles. For acceleration driving mode, TFC factor values reach the maximum level. It is well known that fuel consumption increases while acceleration is due to the need for more power. In addition, some studies show that acceleration level is quite effective on fuel consumption [36, 37]. It is highlighted in another study that the same acceleration level at different speeds has a dissimilar effect on CO<sub>2</sub> or fuel economy [38]. Although the time taken for acceleration in WLTC is less than AIDCs, the TFC factor obtained is higher. This is because the vehicle also accelerates at high speeds in the WLTC test. On the other hand, the TFC factor obtained in AIDCs in cruise driving is about 30% of the value calculated in WLTC. This is because WLTC has high cruise speeds than AIDCs.

## Conclusions

In this study, a methodology that generates artificial cycles based on average speeds reflecting all hours of the day is introduced in order to obtain cycles with features comparable to WLTC. The cycles obtained with this methodology can be considered semi-real in that they are both compatible with average traffic data and include real acceleration distributions.

AIDC, created with artificial instantaneous speeds, includes hourly average travel distances instead of fixed travel distances. For this reason, it is a longer cycle than the WLTC test. AIDCs, which are created according to the 3-month average speeds of Istanbul traffic, have lower highway speeds compared to WLTC. On the other hand, AIDCs obtained according to the limits of the actual speed—acceleration distribution—have a wider acceleration/deceleration range than WLTC.

AIDCs and WLTC are modelled with the AVL Cruise software to compare CO<sub>2</sub> and fuel consumption factors, and engine-operating conditions are analysed. While AIDCs use higher engine load, WLTC runs on a higher engine speed region. CO<sub>2</sub> emission factor for all cycles so close to each other in both urban and rural segments but WLTC has a higher CO<sub>2</sub> factor at the highway segment due to the higher driving speeds. TFC values during acceleration are the highest because of the high power demand for all tests, while AIDCs have low TFC factor than WLTC due to the low cruise speeds.

This study presents a methodology that can serve as an example for future studies to create a driving cycle. Because it is based on average traffic data, it creates a dynamic result which can be modified with changing traffic behaviour. However, as hourly traffic data causes damping of the average speed, this aspect can be further improved.

## Abbreviations

WLTC	Worldwide Harmonized Light-Duty Test Cycle
RDE	Real-driving emission
CO <sub>2</sub>	Carbon dioxide
TFC	Total fuel consumption
V	Vehicle speed
N	Vehicle number

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## Authors' contributions

MA wrote the original draft, made simulations and created the methodology. CS reviewed and edited the paper. All authors read and approved the final manuscript.

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## Availability of data and materials

The data that support the findings of this study are available from Başarsoft Ltd., but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the corresponding author upon reasonable request and with permission of Başarsoft Ltd.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

**Competing interests**

The authors declare that they have no competing interests.

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