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# Developing Real-World Drive Cycles for Heavy-Duty Freight Vehicles using On-Board Diagnostics Data

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**Abstract**

Driving cycles or drive cycles are plots of speed versus time used in vehicle testing to estimate fuel consumption and emissions. They are representative of a typical driving pattern of a vehicle type on a route (terrain). For developing drive cycles, the speed data of a vehicle are collected by the car chase method or using on-board devices (such as global positioning system devices); on-board devices provide more accurate speed data at second-by-second intervals than the car chase method. We used on-board diagnostic (OBD) devices to capture accurate speed–time profiles. About 0.4–0.5 million speed records from two heavy-duty freight vehicles (42 and 48 metric ton trucks) were obtained during their regular real-world operations for over a month on intercity routes in Karnataka, India. A modified random selection approach to sequence microtrips was used to synthesize drive cycles using OBD data. The developed drive cycles for the 42t and 48t trucks had a mean relative error of 8.34% and 9.63%, respectively, within the acceptable limit of 10%. Comparison of the developed drive cycles with the standard Indian and international drive cycles for heavy-duty vehicles showed significant differences in terms of average and maximum speed and duration. Of note, the study was limited to two trucks owing to data collection constraints, such as low on-road population of trucks with OBD-II ports in India and unwillingness of truck operators to allow plugging-in of devices for data collection. Thus, there is a need for similar studies with extensive data collection from multiple vehicles to draw broader conclusions.

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*Keywords:* heavy-duty freight vehicles; on-board diagnostics; microtrips; highway drive cycle

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## 1. Introduction

Currently, India has about 300 million vehicles that together consume 47% of its crude oil consumption. This accounts for about 10% of the nation's total greenhouse gas (GHG) emissions (Mogale et al., 2022). Within the transport sector, goods vehicles account for only 5% of the total vehicular population (Ministry of Road Transport & Highways, 2022) but contribute to around 45% of transport-related emissions (International Energy Agency, 2021). Further, owing to the growth in the e-commerce sector, freight activity is expected to grow five folds by 2050 (NITI Aayog et al., 2021), thereby increasing transport-related GHG emissions.

Since the Paris Agreement was signed at the Conference of Parties (COP 21) held in Paris in 2015, India has committed to climate change mitigation and adoption by submitting its Nationally Determined Contribution (NDC). As per the updated NDC, India is now committed to reduce the emission intensity of its GDP by 45% by 2030 from its 2015 levels (Government of India, 2022). To achieve this, the transport sector should adopt several decarbonization strategies such as improving fuel efficiency, adopting electric vehicles, and using alternative fuels. For these strategies to be adopted, the energy consumption of vehicles needs to be accurately estimated to assess the impact, effectiveness, and efficiency of the strategies. Generally, drive cycles are used to estimate real-world fuel consumption and vehicular emissions (Arun et al., 2017; Bishop et al., 2012; Desineedi et al., 2020; Mayakuntla & Verma, 2018; Quirama et al., 2020).

Typically, a drive cycle is a speed–time profile that represents the driving characteristics of a given vehicle type in a given city/area/terrain (Amirjamshidi & Roorda, 2015; Arun et al., 2017; Desineedi et al., 2020; Kamble et al., 2009; Mayakuntla & Verma, 2018; Nesamani & Subramanian, 2011). The Automotive Research Association of India developed a standard Indian Drive Cycle (IDC) in 1985 based on data collected from Mumbai, Chennai, Bengaluru, and Pune. The cycle is 108 seconds long with an average speed of 21.9 kmph, a maximum acceleration of 0.65 $m/s^2$, and a maximum deceleration of 0.63 $m/s^2$ (Kamble et al., 2009; Ministry of Road Transport & Highways, 2000; Nesamani & Subramanian, 2006). In 2000, the modified IDC (MIDC), with an average speed of 59.3 kmph, a maximum acceleration of 0.833 $m/s^2$, and a maximum deceleration of 1.389 $m/s^2$, was adopted (Ministry of Road Transport & Highways, 2000). These drive cycles are considered to represent the driving characteristics of all drive modes (such as acceleration, cruising, and idling) along all regions. However, the driving characteristics vary significantly with different vehicles and across different regions (André et al., 2006; Mayakuntla & Verma, 2018). Hence, the IDC or MIDC may not represent the driving characteristics of all vehicle types, especially freight vehicles, as they typically operate on highways and have a higher weight, lower speed, and lesser acceleration/deceleration. These drawbacks of standard drive cycles also lead to erroneous estimates of network-level emissions. This highlights the need to develop freight vehicle-specific real-world drive cycles to determine the current energy consumption and vehicular emission levels.

## 2. Literature review

A typical drive cycle comprises a series of vehicle operating conditions—cruise, creep, acceleration, deceleration, and idling (Amirjamshidi & Roorda, 2015; Arun et al., 2017; Desineedi et al., 2020; Kamble et al., 2009; Mayakuntla & Verma, 2018; Nesamani & Subramanian, 2006, 2011). Usually, drive cycles have a duration of 10–30 min, which is sufficient to represent the variations of the real-world driving characteristics while being practical and cost effective for data collection (Amirjamshidi & Roorda, 2015; Desineedi et al., 2020).

To construct a representative drive cycle, the collected drive cycle (or the target drive cycle) is separated into microtrips. A microtrip is the trip between successive halts. It typically includes acceleration and deceleration modes and idling either at the beginning or at the end (Desineedi et al., 2020; Ho et al., 2014; Kamble et al., 2009; Seers et al., 2015; L. Zhang et al., 2021). The representativeness of a drive cycle depends on the quality and quantity of data collected, drive cycle construction method, and assessment parameters used to compare the representativeness of the constructed drive cycle (Quirama et al., 2020).

Driving patterns and drive cycles are described based on parameters related to speed and time, such as average running speed and maximum acceleration and deceleration. These parameters are used to assess the representativeness of a drive cycle to the actual driving characteristics. Commonly used assessment parameters include average speed, average running speed, average acceleration, average deceleration, percentage time spent idling, average number of acceleration−deceleration changes, root mean square acceleration, and positive-acceleration kinetic energy (Amirjamshidi & Roorda, 2015; Arun et al., 2017; Chandrashekar et al., 2021; Desineedi et al., 2020; Ho et al., 2014; Nesamani & Subramanian, 2011).

An early attempt to develop representative drive cycles was made by Kent et al. (1978) in Sydney to compare the representativeness of the US Federal Driving Cycle to Sydney's traffic characteristics and vehicular emissions. The study used the car chase method with a speed recorder to collect speed data. Esteves-Booth et al. (2001) developed a drive cycle for urban roads in Edinburgh, UK. This study also employed the car chase technique using an on-board electronic control module on the instrumented vehicle to collect data (ambient and water temperatures, throttle position, vehicle speed, engine speed, date, and time). The study developed a new statistical method—Traffic Flow IndeX to construct a representative drive cycle using various measurements. Lin and Niemeier (2003) developed drive cycles for three cities in California, USA, to examine the variations in driving patterns across traffic conditions (congested and uncongested) and road types (arterial and freeway). The study used the car chase method to collect second-by-second speed data during the AM, PM, and off-peak hour periods. The drive cycles were constructed using the Markov process theory to sequence the operating conditions. Ho et al. (2014) developed a Singapore Driving Cycle using the car chase method to collect speed and position data along expressways and arterial roads. A semi-random approach was used to select microtrips, and the resultant drive cycle was selected based on 20 assessment parameters, including average number of stops per kilometer and average microtrip duration.

Quirama et al. (2020) developed a drive cycle for buses plying in two Mexican cities. On-board diagnostic (OBD) system, version II (OBD-II), was used to collect data (speed, position, and fuel consumption). They developed an energy-based microtrip method to construct drive cycles that represent real fuel consumption and tailpipe emissions from the vehicles. L. Zhang et al. (2021) developed road type-based drive cycles for passenger cars in Guangzhou, China. Data were collected along arterial roads, highways, and other urban roads using hand-held global positioning system (GPS) devices. Principle component analysis and k-means clustering were applied on the assessment parameters, and the representative drive cycle was selected from a pool of alternative drive cycles based on the Mahalanobis distance and speed acceleration frequency distribution.

Although most initial studies focused on developing drive cycles for passenger vehicles, specifically cars, Amirjamshidi & Roorda (2015) developed drive cycles for light-, medium-, and heavy-duty trucks along freeways and major arterial roads in Toronto, Canada. Seers et al. (2015) compared drive cycles developed for pick-up trucks used for suburban transport and airport operations in Montreal, Canada. The vehicles' OBD-II port was used to collect the vehicle speed over time. In addition, Prohaska et al. (2016) developed drive cycles for class 8 drayage trucks operating at the ports of Southern California, USA. Data loggers were used to collect data from the vehicles' OBD-II port. The data were processed using National Renewable Energy Laboratory's Drive-Cycle Rapid Investigation, Visualization, and Evaluation processing tool. C. Zhang et al. (2021) developed drive cycles for heavy-duty vehicles by implementing decision tree regression. Data from Fleet DNA database related to drayage, long haul, regional haul, local delivery, and transit bus were used along with metrics, such as engine power and fuel consumption, for cycle development.

Similar studies were conducted in India as well to develop drive cycles that account for the heterogeneity in traffic. Nesamani & Subramanian (2006) developed a drive cycle for cars using data from hand-held GPS devices in Chennai, India, to compare the representativeness of the IDC for assessing the impact of real-world driving on emissions. Kamble et al. (2009) developed a drive cycle for urban roads using microtrips extracted from data collected through the car chase method in Pune, India. Nesamani & Subramanian (2011) developed a drive cycle for intracity buses in Chennai, India, using microtrips and collected data using GPS devices. Sharma et al. (2016) used data from on-board emission measurement (OEM) equipment to develop speed-based emission factors for passenger cars, sports utility vehicles, and 16t trucks under Indian driving conditions.

Arun et al. (2017) developed a drive cycle for passenger cars and motorcycles for urban roads in Chennai, India. Hand-held GPS devices were used to collect the second-by-second speed data, and then, eleven assessment parameters were used to construct the most representative drive cycle from microtrips. Mayakuntla & Verma (2018) conducted a study in Bengaluru, India, to develop a drive cycle for passenger cars using the trip segment construction technique. Data for constructing the drive cycle were collected using a Racelogic VBOX data logger. Desineedi et al. (2020) also developed a drive cycle for intracity buses in Chennai by clustering microtrips using the k-means clustering process and Markov modelling process. Second-by-second speed data were collected using hand-held GPS devices. Jin et al. (2020) also attempted to develop a drive cycle for buses in Bengaluru, India, using random sequencing of microtrips. Data were collected from the GPS-based vehicle tracking system used by the transit operator. Recently, Chandrashekar et al. (2021) developed a drive cycle for e-rickshaws in rural and urban areas in Sangareddy region, Telangana. Speed data over time were collected using a GPS data logger. The study tested two approaches—random selection and k-means clustering—to obtain the most representative drive cycle using microtrips.

Table 1 provides a summary of the studies conducted on drive cycle synthesis. Most studies developed drive cycles for passenger vehicles (motorcycles, cars, and buses) on urban roads, commonly employing either the car chase method or hand-held GPS devices. However, few studies developed drive cycles for freight vehicles operating primarily on highways, especially in India.

Table 1: Summary of studies that developed drive cycles

| Study | Year | Country | Vehicle type | Route type | Data collection method |
|---|---|---|---|---|---|
| Kent et al. | 1978 | Australia | Passenger car | Expressway, arterial and sub-arterial roads | Car chase |
| Esteves-Booth et al. | 2001 | UK | Passenger car | Urban roads | Car chase |
| Lin & Niemeier | 2003 | USA | Passenger car | Arterial roads and freeway | Car chase |
| Ho et al. | 2014 | Singapore | Passenger car | Arterial roads and expressway | Car chase and OBD-II port |
| Quirama et al. | 2020 | Mexico | Bus | Urban and suburban roads | OBD-II port |
| L. Zhang et al. | 2021 | China | Passenger car | Arterial roads, highways, and other urban roads | Hand-help GPS device |
| Nesamani & Subramanian | 2006 | India | Cars | Urban roads | GPS |
| Kamble et al. | 2009 | India | Passenger car | Urban roads | Car chase |
| Nesamani & Subramanian | 2011 | India | Buses | Urban roads | GPS |
| Arun et al. | 2017 | India | Passenger car and motorcycle | Arterial roads | Hand-held GPS device and OBD-II port |
| Mayakuntla & Verma | 2018 | India | Passenger cars | Urban roads | Data logger |
| Desineedi et al. | 2020 | India | Buses | Urban roads | Hand-held GPS device |
| Jin et al. | 2020 | India | Buses | Urban roads | GPS-based vehicle tracking system |
| Chandrashekar et al. | 2021 | India | E-rickshaw | Urban and rural roads | Data logger |
| Chen et al. | 2007 | China | Heavy-duty diesel trucks | Residential roads, arterial roads, and highway | GPS |
| Amirjamshidi & Roorda | 2015 | Canada | Trucks | Arterial roads and freeways | Sourced from Ministry of Transportation |
| Seers et al. | 2015 | Canada | Pickup trucks | Suburban roads and airport roads | OBD-II port |
| Prohaska et al. | 2016 | USA | Class 8 drayage trucks | Port area | OBD-II port |
| C. Zhang et al. | 2021 | USA | Class 8 heavy-duty vehicles | US freeways | CAN data sourced from Fleet DNA database |
| Kancharla & Ramadurai | 2018 | India | Trucks | Urban roads | On-board GPS device |
| Sharma et al. | 2016 | India | Trucks, sports utility vehicles, | | On-board emission measurement (OEM) equipment |

| | | |
|---|---|---|
| | and passenger cars | |

Thus, the present study aimed to address the aforementioned gap in literature by developing drive cycles for long-haul trucks (tonnage: 42t and 48t) on Indian highways using data collected from the vehicles' OBD-II port. Although light-, medium-, and heavy-duty trucks should have been included in the study, the scope was limited only to 42t and 48t heavy-duty trucks owing to two main data collection constraints. First, in India, OBD-II ports are mostly found in newer trucks, i.e. 2020 or later models, whose on-road population is low. Second, most truck operators were unwilling to allow plugging-in of devices for data collection citing concerns regarding privacy and trade secrets.

In this paper, Section 3 provides the overall study approach and Section 4 details the data collection process (instruments, technique, vehicles, and routes) and provides a summary of data collected. The step-by-step methodology adopted for the synthesis of drive cycles is described in Section 5. Further, the process of drive cycle construction and comparison with existing drive cycles are described in Section 6, followed by the Conclusions in Section 7.

## 3. Study approach

The study identified popular intercity freight routes in Karnataka, India, through a freight volume count survey. Transport operators servicing along the identified corridor were selected for data collection. OBD devices were plugged in to the trucks. Data relayed from the OBD devices were downloaded using a web interface. The downloaded data were cleaned, collated, and analyzed, and the data were then used as input to synthesize drive cycles. The developed drive cycles of trucks were compared with the standard Indian drive cycle (MIDC) and global heavy-duty drive cycles like World Harmonized Vehicle Cycle (WHVC) and others to ascertain similarities or differences if any.

## 4. Data collection

The speed−time profiles of heavy freight vehicles were collected on intercity routes/highways in Karnataka, India. Details of vehicles, instruments used, routes, and summary of data collected are presented in this section.

### *4.1. Vehicles*

Heavy-duty freight vehicles with a gross vehicle weight (GVW) of 42t and 48t were considered for this study. These trucks are widely used for transportation of building materials for construction activities in India. Both the diesel-powered 2020 model trucks had five axles and a wheel base (tag type) of 6.2 m. The 42t truck had 14 wheels, whereas the 48t truck had 16 wheels. The peak power of the engine driving these trucks was 186 kW. The trucks had a heavy-duty ladder-type frame and were Bharat Stage 6 compliant. Both trucks were approximately 2-years old and recorded a mileage of 110,000 km.

### *4.2. Instruments*

OBD devices are connected to a vehicle's OBD-II port and widely used to monitor vehicle performance. Based on the make and model, they can acquire kinematic data (such as speed), geographic data, engine metrics (such as rpm), and fuel tank metrics. Geographic data include latitude, longitude, and altitude along with the timestamp. In the present study, OBD devices compatible with the trucks described in section 3.1 were used. The OBD devices (Fig. 1) were capable of acquiring speed data along with the geolocation and corresponding date and time. The devices were calibrated to record the data at 1 Hz (one data point per second).

Figure 1: (a) On-board diagnostic (OBD) devices used in the study (left), and (b) an OBD device plugged in the port (right)

A 4G sim card inserted in the OBD devices enabled transmission of the data acquired. A Fleet Management Software compatible with the OBD devices' data transfer protocols was used to remotely access and download the acquired data for further analysis. However, the OBD devices have an inherent (manufacturing) limitation of occasionally recording data at an interval higher than the set frequency. This is mainly due to disruptions in power supply to the OBD device plugged in and network issues. Further, the OBD devices stop data recording and its transfer a few seconds after the vehicle ignition is switched off.

### *4.3. Routes*

Trucks under this study were plying mostly on the highways, i.e., intercity routes. Geographically, the routes were spread across the southern part of Karnataka state in India, through Bengaluru, Mysuru, and Mangaluru cities (Fig. 2 and 3). Data were collected during the typical operations of these trucks, and the authors did not have any control over the routes and assignment of drivers. It was noted that four different drivers with varying experience drove the trucks during the data collection period. In case of both trucks, 70% of the trips started during 1200–2359 hours. Further, the average trip length of the 42t and 48t trucks was 92 (+/- 71) and 120 (+/- 82) km, respectively.

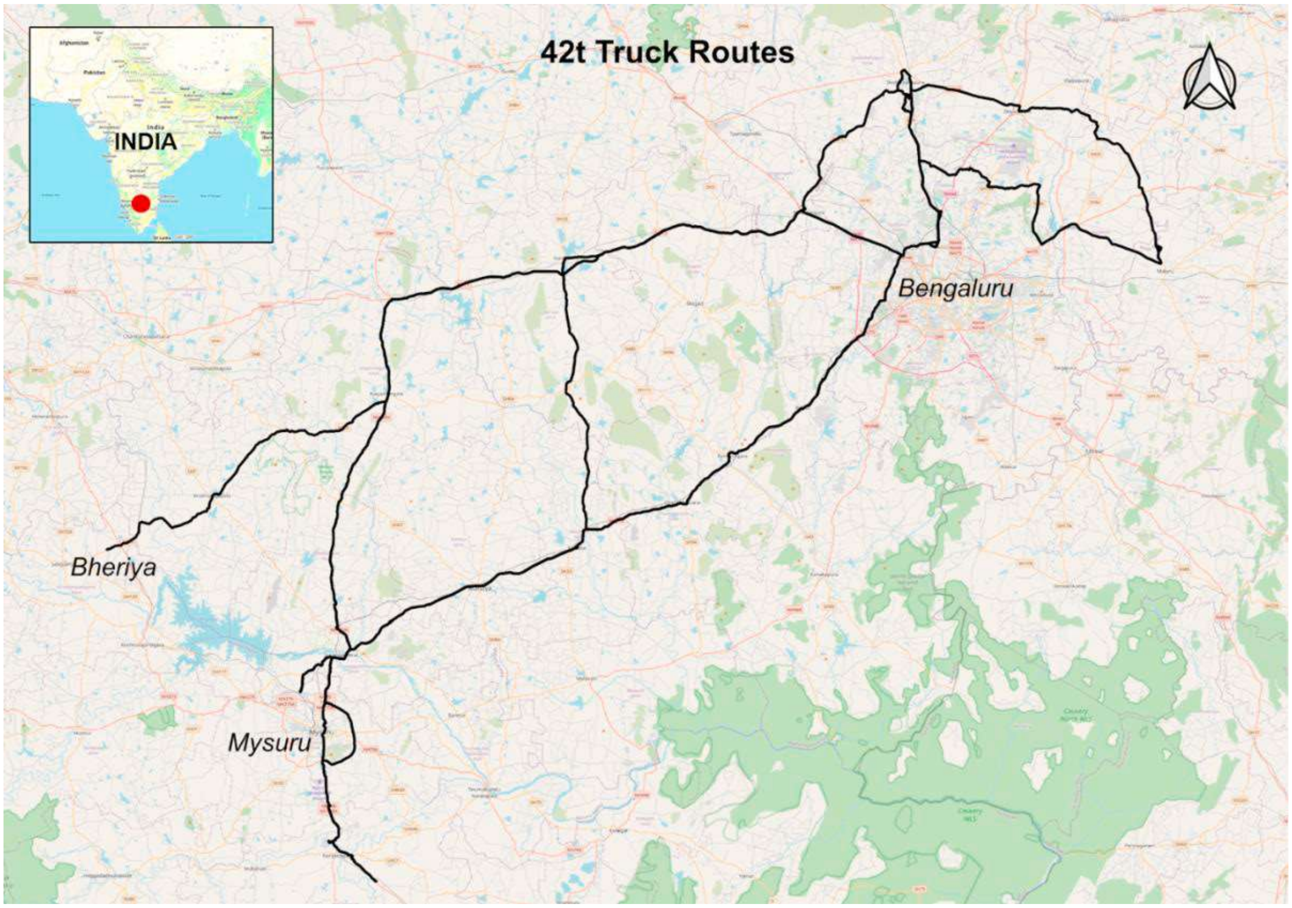


Figure 2: Routes taken by the 42t truck

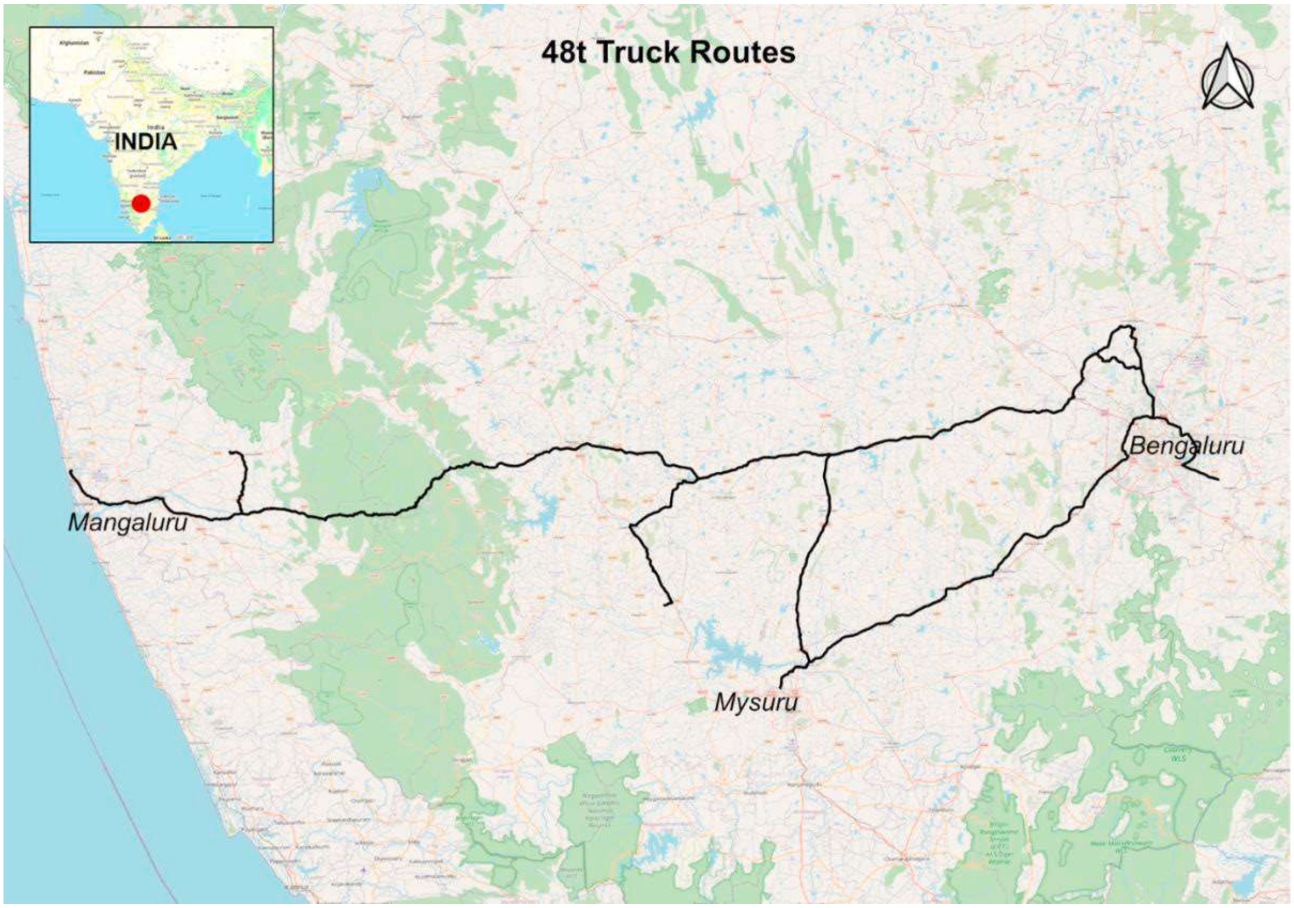


Figure 3: Routes taken by the 48t truck

### 4.4. Summary of data collected

Data from the OBD devices, i.e., instantaneous speed in kmph, geolocation (latitude and longitude), and ignition status (on or off) with timestamps, were collected from the two trucks. Data were collected for 30 continuous calendar days in July−August 2022. Data were cleaned by removing ignition off readings and collated. Table 2 provides a summary of the collected data. The interval between the earliest time at which the ignition status was "on" and the latest time with ignition "on" status before "off" status was taken as one trip, and the trip count was accordingly obtained. The trace of the route taken by the truck on a map platform at corresponding timestamps was also used to corroborate the trip start and end times.

Table 2: Data summary

| Truck | Duration | Number of trips | Distance in km | Number of records |
|---|---|---|---|---|
| 42t | 30 days | 53 | 4,909 | 463,139 |
| 48t | 30 days | 41 | 4,920 | 500,558 |

Of the 463,139 data points collected from the 42t truck, 99.23% had a time interval of 1s. Similarly, of the 500,558 readings from the 48t truck, 76.41% had a time interval of 1s (Table 3).

Table 3: Distribution of time intervals of speed records

| Time interval in seconds | Cumulative% of records | |
|---|---|---|
| | 42t truck | 48t truck |
| 1 | 99.23 | 76.41 |
| 2 | 99.29 | 99.50 |
| 3 | 99.33 | 99.54 |
| 4 | 99.38 | 99.57 |
| Less than or equal to 5 | 99.42 | 99.61 |
| Less than or equal to 10 | 99.58 | 99.72 |
| Above 10 | 100 | 100 |

## 5. Methodology: drive cycle synthesis

Based on the literature review, suitability to data acquired from the OBD devices, and availability of computational infrastructure, the following approach was adopted to synthesize the drive cycles.

Data from the OBD devices were cleaned and collated. Then, 12 assessment parameters selected based on the literature review (Table 4) were calculated for the collated data and termed "target stats." Consistent with the literature, we defined a microtrip as an interval between a zero speed, which is followed by acceleration, and subsequent zero speed including idling (if any) before accelerating. Of note, all idling was not captured and only the idling when the ignition was "on" was captured owing to the functional limitation of the OBD devices. Microtrips in the dataset were identified, and their count was determined.

Table 4 Assessment parameters

| Parameter | Unit | Description |
|---|---|---|
| Average speed | kmph | Average speed of all speed records |
| Average running speed | kmph | Average speed of all speed records excluding zero speeds |
| Percentage idle time | % | Idling time of vehicle (speed = 0 kmph) |
| Average acceleration | $m/s^2$ | Average acceleration of all speed records |
| Percentage acceleration | % | Time during which acceleration > 0.1 $m/s^2$ and speed > 5kmph |
| Root Mean Square (RMS) acceleration | $m/s^2$ | Measures driver aggressiveness; $\sqrt{acceleration^2}$ |
| Average deceleration | $m/s^2$ | Average deceleration of all speed records |
| Percentage deceleration | % | Time during which deceleration greater than 0.1 $m/s^2$ and speed above 5kmph |
| Positive acceleration kinetic energy | $m/s^2$ | Energy required for accelerating a unit distance |
| Percentage creep | % | Acceleration and deceleration less than 0.1 $m/s^2$ and speed less than 5kmph |
| Percentage cruise | % | Acceleration and deceleration less than 0.1 $m/s^2$ and speed more than 5kmph |
| Percentage acceleration to deceleration and vice-versa | % | Number of times vehicle shifted from acceleration to deceleration and vice versa |

Candidate drive cycles were constructed by sequencing two randomly chosen microtrips from the dataset in each iteration. The 12 assessment parameters were calculated for the candidate drive cycles and were called "test stats." The mean relative error (MRE) was calculated as the arithmetic mean of the relative difference between individual target stats and test stats and was expressed in %.

$$MRE = \frac{\sum_{i=1}^{12} \frac{(a_i - A_i)}{A_i}}{12},$$

where $a_i$ and $A_i$ are test and target stats, respectively, and i is the corresponding assessment parameter.

The candidate drive cycle with the least MRE among 50,000 iterations was shortlisted, and its distance and duration were noted. This process was consecutively repeated for sequencing cases with 3−10 randomly chosen microtrips, and in each sequencing case, the candidate drive cycle with the least MRE was shortlisted. All shortlisted candidate drive cycles were compared for MRE and duration, and the one with the least MRE was chosen as the final drive cycle of the truck. The flowchart of the procedure is presented in Fig. 4 below.

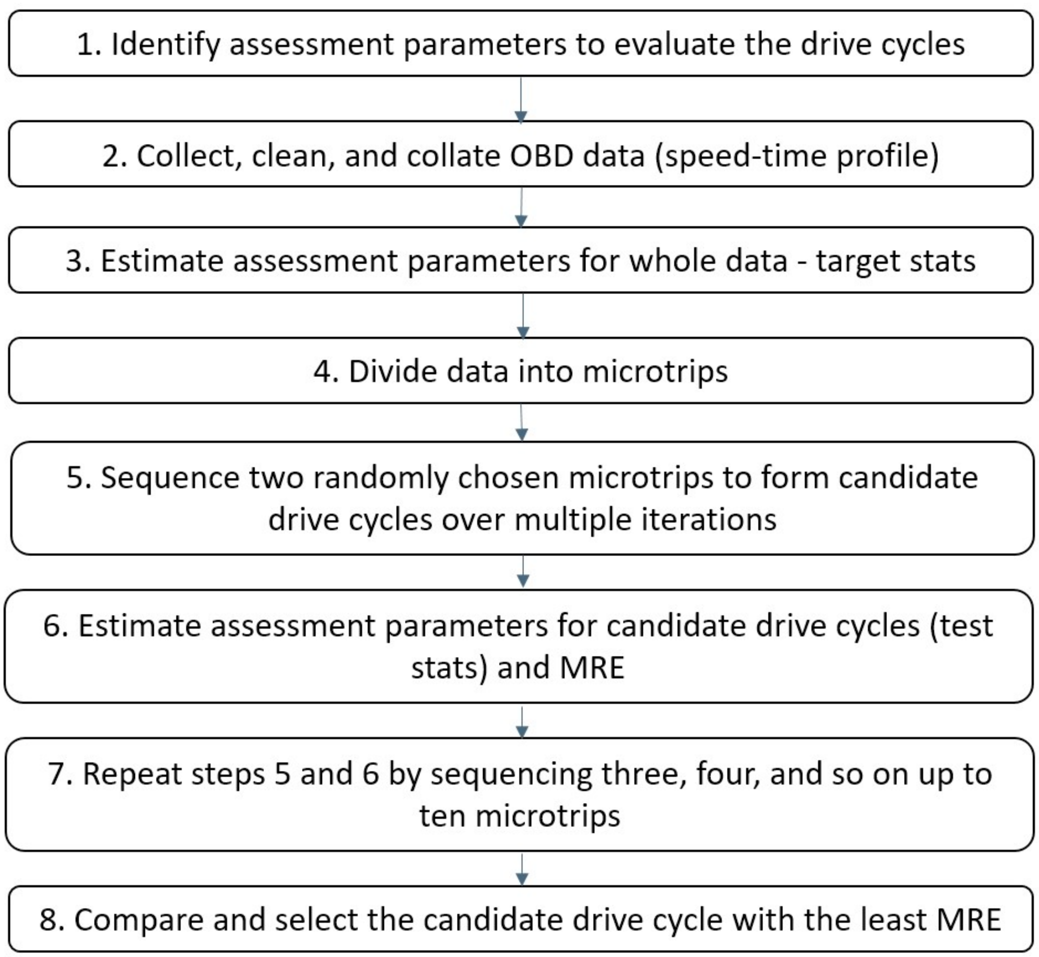


Figure 4: Methodology: drive cycle synthesis

A python script was written to synthesize the drive cycles, as per the above described procedure. A 160-core high-performance virtual computing cluster was employed for the synthesis. We limited to 50,000 iterations and sequencing up to 10 microtrips due to computational time. Moreover, with a higher number of microtrips in the sequence, the duration of the candidate drive cycles increases drastically, which is undesirable.

The adopted procedure is in principle similar to the prevalent method of synthesis of drive cycles by random selection of microtrips. However, it employs a two-level search for identifying the drive cycle with the least MRE. In the first level, it identifies and shortlists the candidate drive cycle with the least MRE in each of the nine sequencing cases (2−10 microtrips), and in the second level, it compares the shortlisted candidate drive cycles to identify the one with the least MRE as the final drive cycle of the truck.

## 6. Drive cycle: construction and discussions

### *6.1. 42t truck drive cycle*

As per the procedure outlined in section 4, 463,139 speed records obtained from 53 trips of the 42t truck were cleaned and collated, and target statistics (Table 5) were estimated. Microtrips in the dataset were identified as per the defined criteria, and accordingly, 2,867 microtrips were found. Two, three, and similarly up to ten microtrips were randomly selected from among these 2,867 microtrips and sequenced to construct the candidate drive cycles. Candidate drive cycles with the least MRE in each sequencing case were shortlisted, and their duration was noted (Fig. 5).

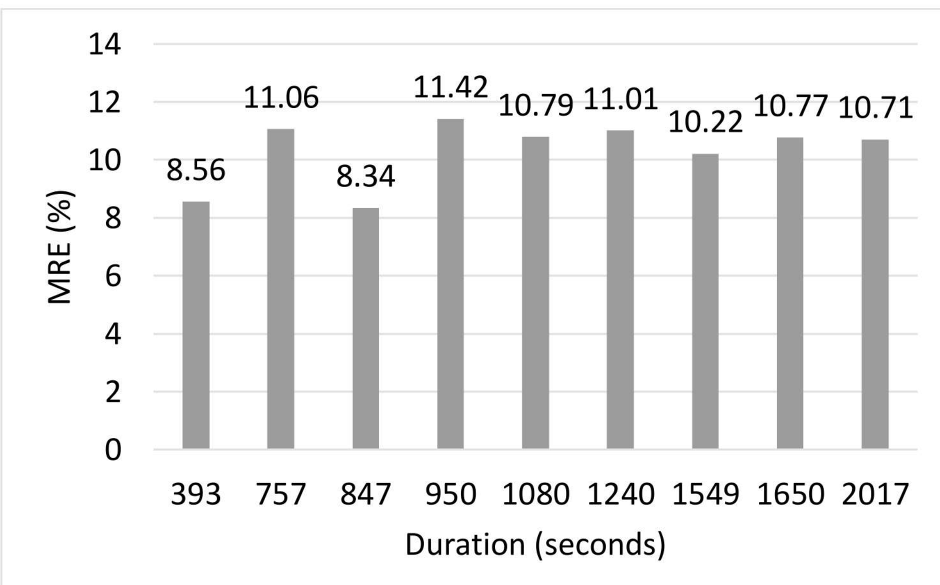


Figure 5: Comparison of candidate drive cycles (42t truck)

As evident from Fig. 5, the candidate drive cycle with 847 s duration had the least MRE of 8.34%. The same was selected as the drive cycle for 42t truck. The speed−time profile of the selected drive cycle is presented in Fig. 6. The drive cycle corresponded to a distance of 8.5 km. The 12 assessment parameters estimated for the drive cycle (Fig. 6) are tabulated in Table 5.

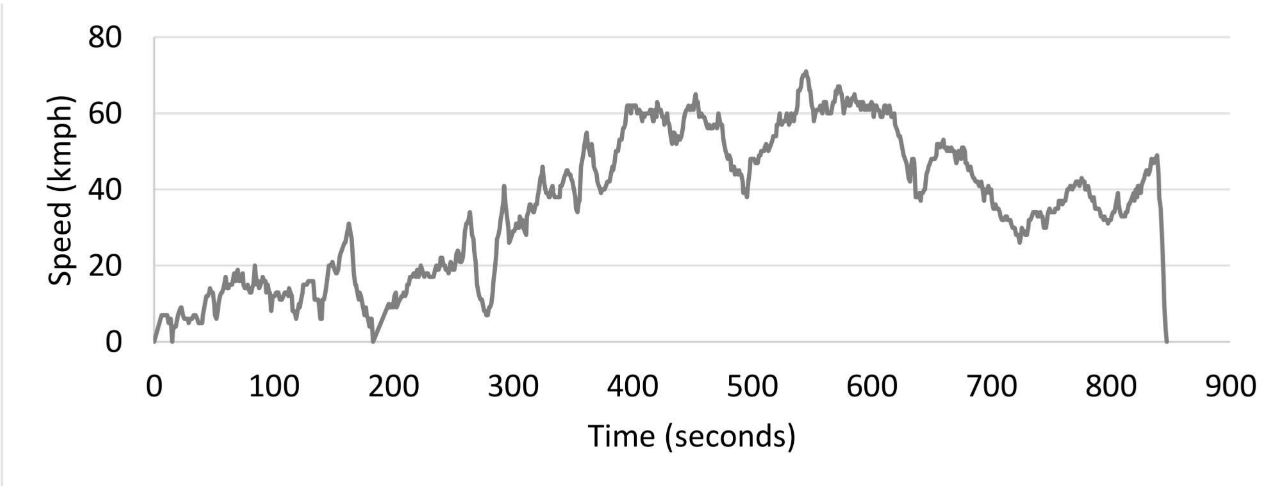


Figure 6: Drive cycle of the 42t truck

Table 5 Target stats and test stats of the 42t truck

| Parameter | Unit | Target stat | Test stat |
|---|---|---|---|
| Average speed | kmph | 35.5615 | 36.2892 |
| Average running speed | kmph | 35.7874 | 36.4208 |
| Percentage idle time | % | 0.6312 | 0.3615 |
| Average acceleration | $m/s^2$ | 0.4766 | 0.4638 |
| Percentage acceleration | % | 36.5749 | 36.6701 |
| RMS acceleration | $m/s^2$ | 0.5712 | 0.5405 |
| Average deceleration | $m/s^2$ | 0.5379 | 0.5137 |
| Percentage deceleration | % | 32.8369 | 33.0519 |
| Positive-acceleration kinetic energy | $m/s^2$ | 0.3341 | 0.2382 |
| Percentage creep | % | 0.6731 | 0.7237 |
| Percentage cruise | % | 28.1585 | 28.5886 |
| Percentage acceleration to deceleration and vice-versa | % | 21.1443 | 20.6521 |

The average speed of the truck was 35.56 kmph, with less than 1% idling. The truck was mostly observed to be accelerating (36.57%) and decelerating (32.83%), followed by cruising (28.15%), with a very low share of creeping (less than 1%).

### 6.2. 48t truck drive cycle

Drive cycle synthesis of the 48t truck using 500,558 speed records obtained from 41 trips was done in a similar manner to the 42t truck. Overall, 2,275 microtrips were found in the dataset and were used for the synthesis of drive cycles in different sequencing (2–10) cases. Fig. 7 shows the comparison of the candidate drive cycles.

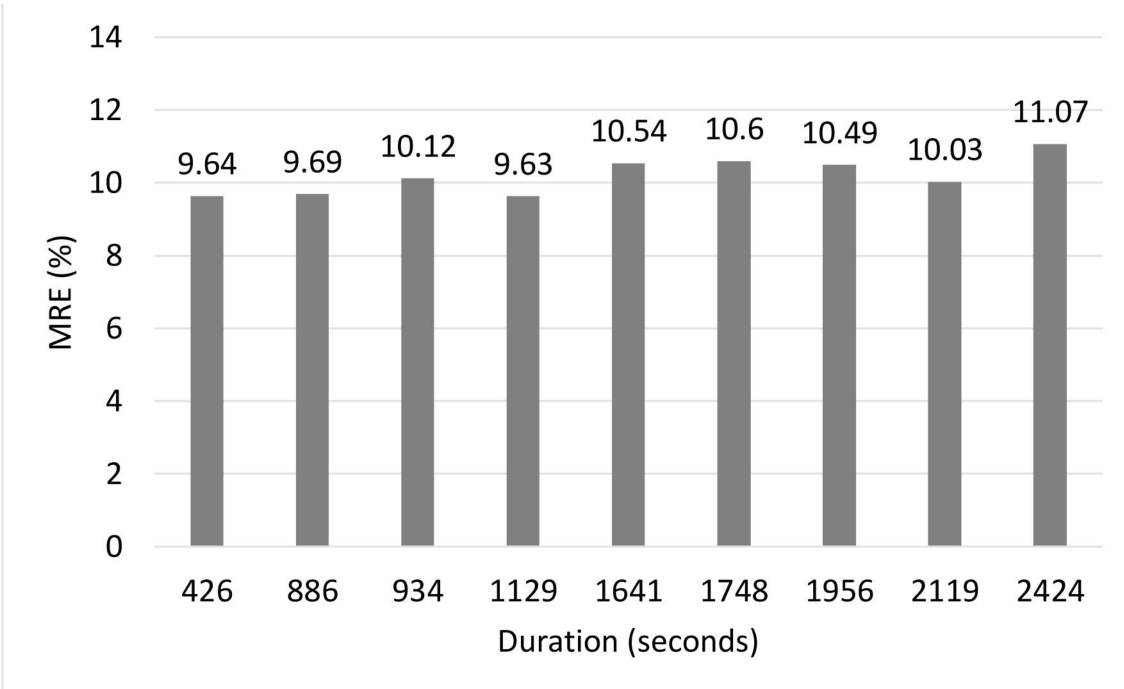


Figure 7: Comparison of candidate drive cycles (48t truck)

Among the candidate drive cycles, the one with 1,129 s duration was found to have the least MRE of 9.63%. Further, the same was selected as the drive cycle of the 48t truck (Fig. 8), which corresponded to a distance of 11.1 km. Table 6 compares the test stats of the drive cycle (Fig. 8) with the target stats.

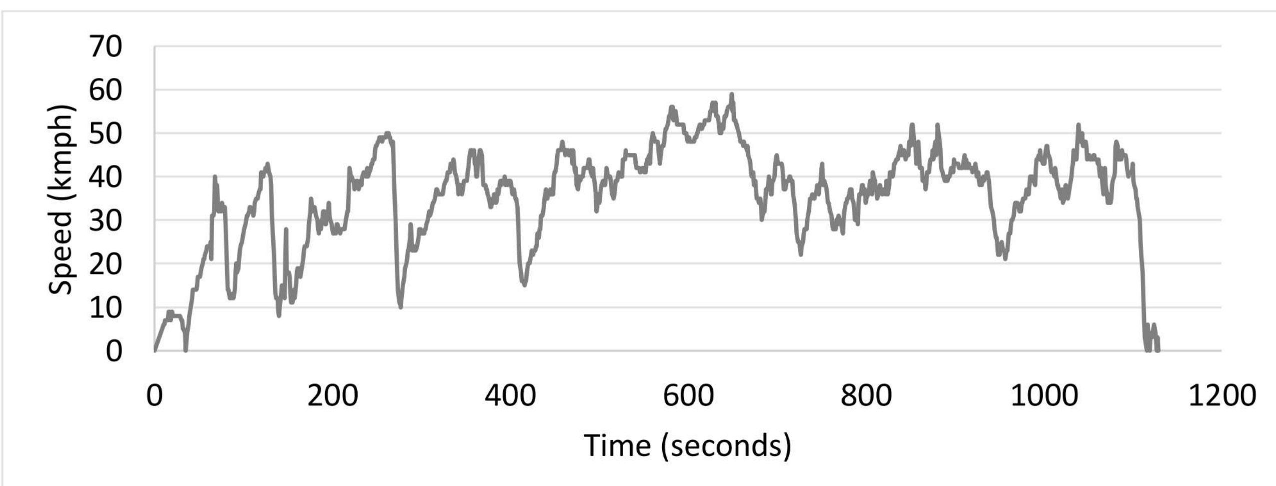


Figure 8: Drive cycle of the 48t truck

Table 6 Target stats and test stats of the 48t truck

| Parameter | Unit | Target stat | Test stat |
|---|---|---|---|
| Average speed | kmph | 34.2705 | 35.7629 |
| Average running speed | kmph | 34.4294 | 35.9236 |
| Percentage idle time | % | 0.4614 | 0.4472 |
| Average acceleration | $m/s^2$ | 0.4303 | 0.4351 |
| Percentage acceleration | % | 34.0818 | 35.7206 |
| RMS acceleration | $m/s^2$ | 0.5107 | 0.5101 |
| Average deceleration | $m/s^2$ | 0.4938 | 0.5188 |
| Percentage deceleration | % | 30.0243 | 31.1548 |
| Positive-acceleration kinetic energy | $m/s^2$ | 0.2825 | 0.0761 |
| Percentage creep | % | 0.6228 | 0.6266 |
| Percentage cruise | % | 33.8872 | 31.5129 |
| Percentage acceleration to deceleration and vice-versa | % | 17.3824 | 18.8172 |

The average speed of the 48t truck was 34.27 kmph, with negligible idling (<1%). The truck was observed to be mostly accelerating (34.08%), followed by cruising (33.88%) and deceleration (30.02%). The average speed, acceleration (0.43 $m/s^2$), and deceleration (0.49 $m/s^2$) of the 48t truck were slightly lower than those of the 42t truck (35.56 kmph, 0.47 $m/s^2$, and 0.53 $m/s^2$, respectively), which may be attributed to the additional 6t load.

### *6.3. Comparison*

MIDC is the legislative Indian drive cycle used for vehicle testing and estimation of emissions. The constructed drive cycles of the 42t and 48t trucks were compared with the MIDC to detect similarities or differences (Fig. 9).

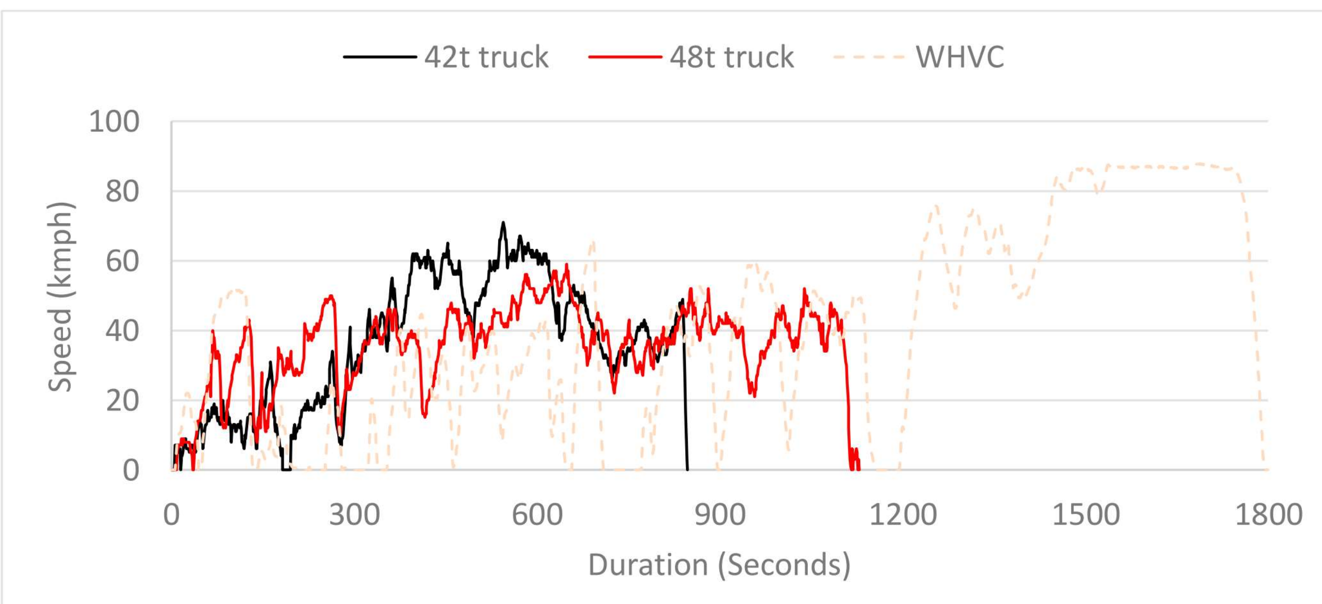


Figure 9: Comparison of the 42t and 48t drive cycles with MIDC and World Harmonized Vehicle Cycle-India

In terms of duration, the 42t truck drive cycle was about 5 mins (333 s) shorter than the MIDC. However, the 48t truck drive cycle with 1,129 s duration was comparable to the MIDC of 1,180 s. The average speed of the 42t and 48t truck drive cycles, i.e., 36.28 and 35.76 kmph, respectively, was comparable to that of the MIDC (32.51 kmph). However, the maximum speed of the 42t (71 kmph) and 48t drive cycles (59 kmph) was lower than that of the MIDC (90 kmph). This is because the MIDC was developed for four-wheelers, such as passenger cars, which have a low tonnage, thus making the comparison of drive cycles developed in this study with local and international heavy-duty drive cycles necessary.

The World Harmonized Vehicle Cycle (WHVC) is globally used for testing of commercial vehicles, as it contains separate rural highway and motorway sections. The developed 42t and 48t truck drive cycles were 953 s and 671 s shorter than the WHVC. Further, the average speed of the WHVC (40.13 kmph) was higher than that of the 42t (36.28 kmph) and 48t (35.76 kmph) truck drive cycles. This indicates that heavy-duty truck speeds on Indian highways are 9 to 11% lower than the global commercial vehicle speeds (WHVC). A possible reason for the lower speeds of trucks could be overloading of trucks, which is prevalent in the Indian scenario, followed by road and traffic conditions.

The Urban Dynamometer Driving Schedule for Heavy Duty vehicles (HD-UDDS) developed by the U.S. EPA, Heavy Heavy-Duty Diesel Truck (HHDDT) drive cycle developed by the California Air Resources Board, and Japanese drive cycle for diesel and gasoline vehicles with a GVW greater than 3.5t developed in 2005 (JE05) were also considered for comparison (Table 7). Notably, vehicles with a GVW above 11.79t are considered heavy-duty vehicles.

Table 7 Comparison with international heavy-duty drive cycles

| Metric | 42t truck | 48t truck | HD-UDDS | HHDDT | JE05 |
|---|---|---|---|---|---|
| Duration (s) | 847 | 1,129 | 1,063 | 2,083 | 1,829 |
| Distance (km) | 8.5 | 11.1 | 8.9 | 37.2 | |
| Average speed (kmph) | 36.28 | 35.76 | 30.2 | 64.2 | 26.9 |
| Maximum speed (kmph) | 71 | 59 | 93.3 | 95.4 | 88.0 |

The 42t truck drive cycle was similar to the HD-UDDS in terms of distance (8.5 and 8.9 km, respectively), but its speed and duration were different from the three drive cycles considered for comparison. The average speed was observed to be 16.7% and 25.8% higher than that of the HD-UDDS and JE05, respectively, but 77% lower than that of the HHDDT. The duration of the 48t truck drive cycle (1,129 s) was comparable to that of the HD-UDDS (1,063 s). However, the average speed was 15.5% and 24.7% higher than that of the HD-UDDS and JE05 cycles, respectively, and 80% lower than that of the HHDDT. Similarly, the acceleration and deceleration of the developed drive cycles of trucks differed from that of the MIDC and WHVC. These differences cumulatively lead to different fuel consumption and emission estimates, thereby highlighting the importance of the developed drive cycles.

Notably, the representativeness of the developed drive cycles is limited in terms of the number of trucks, as they are based on one truck each. However, their representativeness in terms of driver experience, data quantum, and accuracy is reasonable, given the data captured drivers of varying experience over 1 month (~5000-km distance; 1-s recording frequency). This study contributes to the literature by developing drive cycles for two different vehicles, i.e. 42t and 48t, of the same category (heavy-duty goods vehicles), which primarily operate on intercity routes.

## 7. Conclusions

Most drive cycles developed for the Indian context focus on passenger vehicles, such as two-wheelers, three-wheelers, and cars, on urban roads. The present study contributes to the literature by developing drive cycles of heavy-duty freight vehicles (42t and 48t trucks) on highways. OBD devices, which provide accurate and reliable information on vehicle performance, were used in this study to collect speed data of the heavy-duty freight vehicles. The speed data of the 42t and 48t trucks on intercity routes were collected during their normal (real-world) operations spanning over a month. Over 99% of the 42t truck and 76% of the 48t truck speed data collected had a frequency of 1 s, and this detailed data were then fed into the drive cycle synthesis algorithm as the input. The synthesis methodology based on random selection of microtrips was adopted with few modifications. Candidate drive cycles of durations ranging between 300 and 2,500 s were synthesized, and one with the least MRE was selected as the final drive cycle.

The developed drive cycles of the 42t and 48t truck had an MRE of 8.34% and 9.63%, respectively, which is within the desired limit of 10% or lower. The drive cycle for the 42t truck had an average speed of 36.28 kmph, and that for the 48t truck was 35.76 kmph. These developed drive cycles were compared with the standard Indian drive cycle (MIDC), WHVC, and three international drive cycles of heavy-duty vehicles (HD-UDDS, HHDDT, JE05) and were found to be different.

Unlike passenger vehicles, for freight or commercial vehicles, payload influences speed and other vehicle performance metrics. Therefore, information about payload during each trip can be used to segregate data and develop different drive cycles for different loading conditions, such as empty, full load, and partial load.

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