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# Strategies for deploying zero-emission bus fleets: Development of real-world drive cycles to simulate zero-emission technologies along existing bus routes

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## Background

The public health risks of diesel exhaust are motivating a technology transition in urban bus fleets. Today, nine out of ten people worldwide breathe polluted air, according to the World Health Organization (2018). The transportation sector is a significant contributor to outdoor air pollution and is estimated to have contributed to 385,000 premature deaths in 2015.

Approximately 83 percent of these are linked to diesel exhaust from mobile sources. To reduce the contribution of diesel bus exhaust to air pollution, cities are moving towards soot-free, low-carbon, and zero-emission technologies.

Climate change mitigation is another motivating factor behind this technology transition. The transport sector produced 7.0 Gt of $CO_2$-equivalent direct greenhouse gas (GHG) emissions in 2010, equivalent to approximately 23% of total energy-related $CO_2$ emissions (6.7 Gt $CO_2$) (Intergovernmental Panel on Climate Change, 2018). Growth in GHG emissions has continued since the late 2000s despite more efficient vehicles and policies adopted to address the issue (Intergovernmental Panel on Climate Change, 2018). Meanwhile, worldwide consumption of fossil diesel fuel by on-road vehicles has more than doubled since 1990 (International Energy Agency, 2017). In addition to the

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issues posed by $CO_2$ emissions, black carbon (BC) from diesel engine exhaust results in severe impacts on the climate, as the particles produce significant near-term climate warming. Heavy-duty vehicles accounted for 78% of on-road diesel BC emissions in 2017, though they made up less than a quarter of the diesel vehicle fleet (Miller & Jin, 2018). The elimination of diesel BC is a key to slowing the rate of global warming and meeting the 1.5°C to 2°C warming target set by the Paris Agreement (Shindell et al., 2017). The climate impacts of transportation-related activity provide motivation for the transition to soot-free, low-carbon, or zero-emission transport.

Zero-emission buses are an attractive alternative technology for mitigating the impact of transportation on urban air quality. Not only do zero-emission engines eliminate near-road exposure to carcinogenic diesel exhaust, but they also are as much as 4 times more energy efficient compared to diesel engines. Battery electric buses that utilize depot-charging or en-route charging are widely deployed today. Other forms of zero-emission technology are also experiencing growth, particularly electric trolleys[1] and hydrogen fuel cell vehicles.

Almost 425,000 electric buses, the vast majority in China, are on the road today. China's National Ten Measures (The State Council, 2013) requires 60% of new buses in major cities be new energy vehicles (NEV), defined as battery electric, plug-in hybrid electric, and fuel cell vehicles. Many major cities and regions throughout China aim to transition 80% of new or existing vehicles to new energy vehicles by 2020, including Hainan, cities in the Pearl River Delta, Harbin, and Changsha.

California has implemented its Innovative Clean Transit regulation (California Air Resources Board, 2018) which mandates that 100% of buses purchased by public transit agencies must be zero-emission by 2029 and sets a goal to transition all buses to zero-emission by 2040. Many California transit agencies have committed to fully transitioning to 100% zero-emission bus fleets by 2030, such as Los Angeles Metro (Los Angeles County Metropolitan Transportation Authority, 2019) and Santa Monica Big Blue Bus (Big Blue Bus, n.d.).

Volume targets are relatively easy to set, but the procurement and deployment of zero-emission buses requires significant effort and proper planning. Fleet-wide planning is necessary to determine the appropriate vehicle technology, infrastructure, and operations that will deliver range and performance equivalent to diesel-powered buses along any given route. This planning will inform estimates of and decisions about such details as optimal battery size, charging strategy, charge-point locations, route distance, route-specific energy usage, battery reserve capacity, expected battery degradation, scheduling, and other factors that will shape vehicle performance. A failure to account for air-conditioning load or charging speed when selecting battery size, for example, can lead to purchasing buses with insufficient range, which would result in the need for additional buses. A poor choice of vehicle technology and charging strategy can adversely impact the operational performance of the fleet and lead to higher costs, decreased rider satisfaction, and unexpected changes in fleet capacity.

Lessons learned from the early deployment of electric bus fleets in Chinese cities show the consequences of inadequate planning. In Shenzhen, Beijing, Wuhan, Qingdao, and Chongqing, 1.5 to 2 battery-electric buses were needed to provide the same level of service as an existing diesel or CNG bus. For plug-in hybrid electric buses, 1 to 1.8

1 Electric trolley buses are powered by electricity from overhead wires.

were needed to provide the same level of service (Li, 2018). Planning can reveal where alternative charging strategies can keep replacement ratios and costs to a minimum.

## Route-level Total-Cost-of-Ownership Modeling

A route-level total cost-of-ownership (TCO) modeling framework can determine the total cost of the vehicles and infrastructure required to transition a single route entirely to zero-emission technology. Fleet operators can select the appropriate vehicle technology and charging strategy to meet the performance of existing vehicles. By looking across all routes, fleet operators can establish operation schedules, determine financing and procurement needs, and ascertain the required staff training to successfully deliver a fleet-wide transition.

The TCO modeling framework consists of three components: route-level drive cycle development, vehicle simulation, and a TCO assessment. This paper identifies methods for developing route-specific drive cycles in a large-scale urban bus fleet. A drive cycle in this context is a representative profile of driving conditions along a single bus route. This profile serves as an input to a model simulation of the energy consumption of currently used or alternative bus technology deployed along the route. The profile can also be useful in chassis dynamometer testing, which simulates the driving conditions of a route in a laboratory setting. Multiple bus engine technologies can be tested and compared on a chassis dynamometer to determine their relative environmental and energy performance.

Drive cycle development enables a wide array of analytical tools that can shape decisions around technology selection for a given route. Key indicators of operational performance can include energy consumption, vehicle range, and cost. These indicators can identify minimum technology requirements, battery degradation rate, and other important constraints. These comparisons inform decisions on the minimum technology specifications for vehicles to be included in future tenders to electrify a route, as well as the infrastructure planning and investments necessary to support the technology selected. This information can be utilized for operational planning to produce a deployment schedule by route and depot, and to accommodate constraints on technology, infrastructure, or financing. Thus, drive cycle development is fundamental to fleet-wide planning for zero-emission bus deployment.

The Bangalore Metropolitan Transport Corporation (BMTC), the largest public operator of transit buses in India, serves as a case study for this paper. BMTC owns and operates 6,500 buses, which the Karnataka state government aims to transition to 100% zero-emission vehicles by 2030. BMTC has requested an Expression of Interest from manufacturers to deliver 1,500 electric buses over the next three years (Bangalore Metropolitan Transport Corporation, 2019). BMTC has also been selected to receive support for the procurement of 300 electric buses under the Government of India's Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME-II) program (Department of Heavy Industry, 2019). In support of these efforts, the ICCT is developing a route-level TCO model to inform BMTC's decisions regarding routes, depots, and fleet procurement. The lessons from the planning, procurement, and deployment strategies will be used inform future deployments of zero-emission buses in Bangalore and other cities.

## Route Cycle Development

For a simulation to accurately represent the real-world performance of a new technology, fleet operators must have access to real-world operational data that captures the performance of existing buses over existing routes. Most large, professionally managed fleets use GPS tracking and other intelligent transport systems (ITS) to monitor and report on fleet performance.  A route-level cycle development tool allows fleet operators to utilize the large datasets produced by ITS and condense the information into representative drive cycles of individual routes.

The three steps taken in the development of a representative route-level drive cycle are illustrated in Figure 1. First, operational performance data are collected from buses traveling along these routes. Second, the data are reviewed to ensure data contained in the cycle development database are complete and contain valid data points. Third, a cycle development tool processes the data to obtain route-level drive cycles. The following sections explains each of these steps in detail.

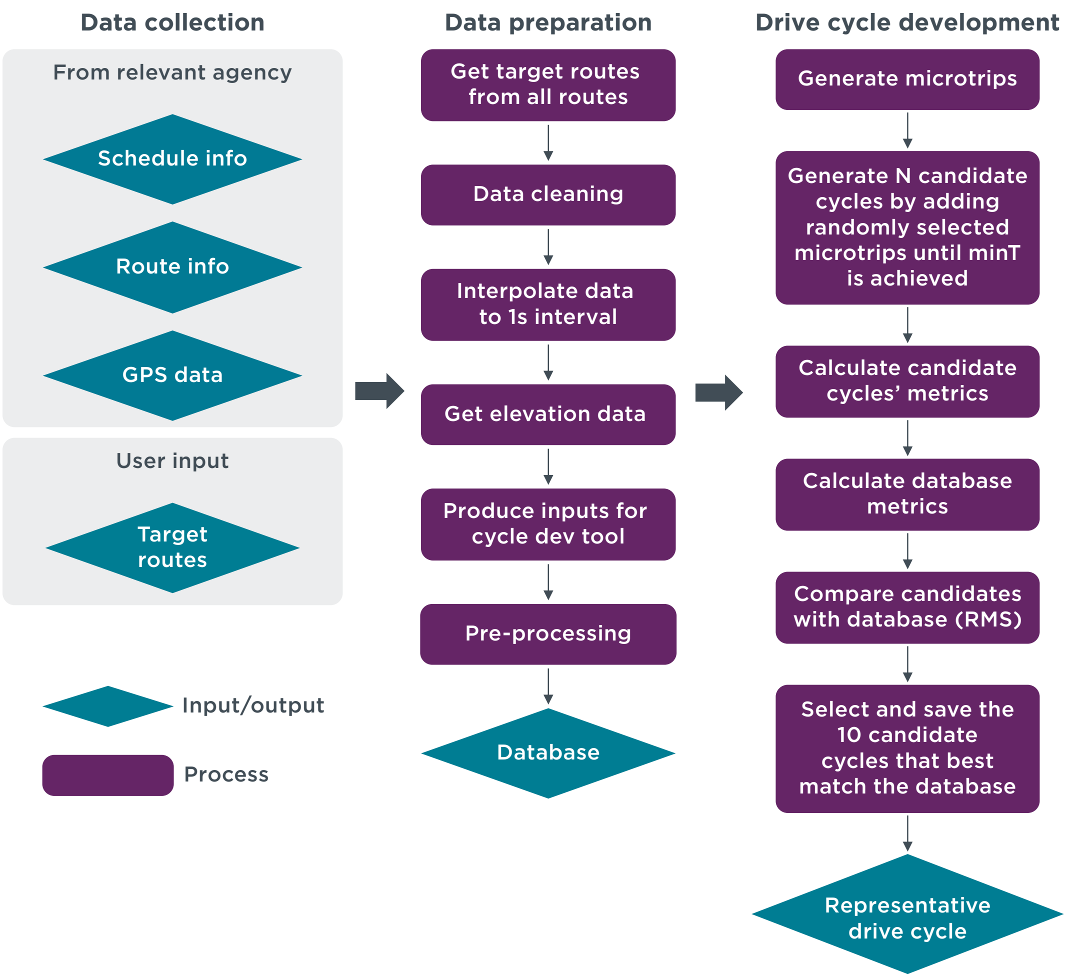


**Figure 1.** Data analysis workflow

### Data collection

Data on time, speed, and elevation are collected from a single bus or multiple buses to develop a representative drive cycle of an individual route. These data are available from most commercial ITS services. If elevation data is not available, longitude and latitude data can be used to extract elevation information from other data sources. The data should ideally reflect bus operations over the course of two weeks to one month and reflect a collection frequency of at least once per second (1Hz). Less frequent data collection is still useful but loses the precision necessary for technology simulation.

Additional fleet operations and performance data are required to develop multiple drive cycles simultaneously for buses operating along a complete route network. The data required, which are typically available from commercial ITS systems, include: [2]

- Total number of buses, each with a unique identifier, serving each route;
- Total length of each route;
- Global Positioning System (GPS)-based vehicle tracking data for each bus traveling each route. These data include date, time, bus or schedule identifier, route identifier, latitude, longitude, speed, and elevation. Latitude and longitude data alone can be used to derive elevation data or to validate the quality and consistency of elevation and route data;
- Schedule information for routes and buses, such as the start and end time of when a bus is in active service and, if available, the average time spent at bus stops along a route; and
- Latitude and longitude of all stops along a route, including origin, destination, and intermediate points. A shapefile for chosen routes, a spreadsheet with similar information, or maps of routes with supplemental origin and destination location data will suffice.

In the case of Bangalore, GPS data is available for buses on all routes operated by BMTC. Each bus is equipped with a GPS device with a unique identifier. This case study uses data spanning a month with GPS coordinates recorded over 10 second intervals. Date, time, latitude, longitude, and speed are collected at each timestamp and location. Additional available data include route and schedule information, such as a unique identifier for each route, latitude and longitude of points along the route, and bus schedules.

## Data preparation

The goal of the data preparation step is to develop a suitable database to serve as an input into a cycle development tool. This ensures that all data contained in the cycle development database are complete and contain valid data points. The cleaning and interpolation process can vary according to the quality of available data and the frequency of which the data was gathered. Data cleaning could involve, for example, removing days with no data, removing days with duplicate data, removing times when the buses are not running, or removing invalid data with unrealistic latitude and longitude measurements. Interpolation of data can be necessary when the data gathering frequency is lower than the recommended 1Hz. These steps ensure high quality inputs into the drive cycle algorithm.

Third-party elevation data, such as the Google Elevation API service (Google Elevation API, 2019), can validate raw elevation data, capture elevation based on raw latitude and longitude data given by GPS tracking, and interpolate elevation and location at higher

2 Depending on project goals and data quality (e.g. whether data provider has QA/QC for GPS data provided and how clean the data is for our purpose), some of these data needs can be relaxed.

resolutions. The cycle development tool requires 1Hz GPS tracking data, or data at 1s intervals, while the BMTC provides data at 0.1Hz, or at 10s interval resolution. For this case study, the Google Maps Elevation application is used to determine elevation from GPS tracking coordinates provided by BMTC. Linear interpolation is then utilized to turn coarse resolution location and elevation data into 1Hz measurements. The time, latitude, longitude, speed, and elevation data is then converted into a format that can be read by the drive cycle development tool.

At this stage, the cleaned GPS data can be further processed to estimate vehicle speed and road grade by performing the following steps:

1. Data concatenation
2. Speed and altitude data filtering[3]
3. False trip deletion[4]
4. Road grade calculation
5. Road grade filtering

The output of this final step is a database that consists of time, speed, and road grade for all the available operational data. This final database is ready to support the drive cycle development phase.

## Drive cycle development

The drive cycle development method applied in this study is based on well-established techniques. Previous research has supported the development of statistically representative drive cycles based on a random concatenation of microtrips from large experimental datasets (Nine et al., 1999; Gautam et al., 2002). The first step in this approach is the separation of data into multiple microtrips, defined as any portion of activity that starts and ends at a vehicle speed of zero. The method proceeds with the generation of a user-defined number of microtrip sequences, or "candidate cycles,"[5] built by randomly concatenating microtrips until a cycle of a minimum user-defined time duration is reached.[6]

Once a set of candidate cycles is built, the candidate cycles are compared against the original database using five cycle metrics: average driving speed, standard deviation of driving speed, characteristic acceleration, average positive road grade, and standard deviation of road grade.[7] The root-mean square (RMS) error relative to the original database's metrics is then calculated for each candidate cycle (Delgado-Neira, 2012). Table 1 shows the metrics used, their physical meaning, and their formulas. The candidate with the minimum RMS error, considered to be the most representative of the database, is selected as the final drive cycle. In the last step, idle segments representing bus stops are added between microtrips to finalize the drive cycle's time-speed and time-road grade traces. The final result is a representative drive cycle.

3 GPS data is inherently noisy, especially at low speeds. In this case, a Savitszky-Golay filter is applied to reduce noise.

4 Microtrips in which speeds are lower than 5 kilometers per hour are not used as they are considered false trips.

5 The 10 best cycles are presented to the user when running the tool. The more candidate cycles are generated, the tool would produce a more representative cycle. Same with selecting longer time duration.

6 This analysis uses 60 mins minimum desired time duration.

7 A useful way to characterize vehicle activity over a cycle or a route is by means of its metrics, such as average velocity, standard deviation of velocity, average acceleration, and stops per distance. These metrics provide some information that the speed-time trace cannot give by itself. The metrics chosen were selected based on authors' experience.

**Table 1.** Metrics used in drive cycle development

| Metric | Definition | Equation |
|---|---|---|
| **Average driving speed** | Average speed while driving, not counting vehicle stops | $\overline{V}_{no\ idle} = D/(T - t_{idle})$ |
| **Standard deviation of driving speed** | Quantifies transient driving | |
| **Characteristic acceleration** | Measures the inertial work to accelerate and/or raise the vehicle per unit mass per unit distance | $\tilde{a} = \frac{1}{D} \sum_{i=2}^{N} [\frac{1}{2}(v_i^2 - v_{i-1}^2) + g(h_i - h_{i-1})]^+$ |
| **Average positive road grade** | Measures the work per unit distance while climbing hills | $\overline{G}_+ = \frac{1}{D} \times \int_0^D G)^+ \, ds \cong \frac{1}{D} \times \sum_{G_i>0} G_i \times \Delta S_i$ |
| **Standard deviation of road grade** | Measures the variability of the road grade | |
| **Root-mean square error** | Measures how far and concentrated the drive cycle metrics are to the ones of the original database | $RMS = [\sum_{k=1}^{n} \left(\frac{M_{k,cd} - M_{k,db}}{M_{k,db}}\right)^2]^{\frac{1}{2}}$ |

*Notes*: *D: total distance; T: total time; $t_{idle}$: idle time; V: speed; g: gravity constant; h: altitude; G: road grade; s: distance; M: metrics; db: database; cd: candidate.

The process of producing a drive cycle from GPS data is illustrated in Figure 2 using data from BMTC. GPS data from multiple buses operating over a single route over a given period of time are used as input. The tool output is a relatively short drive cycle that is based on the metrics listed in Table 1 and is representative of the original route. The generated cycle is suitable for identifying the energy efficiency or fuel consumption characterization of the buses running on the selected route using chassis dynamometer testing or vehicle simulation software.

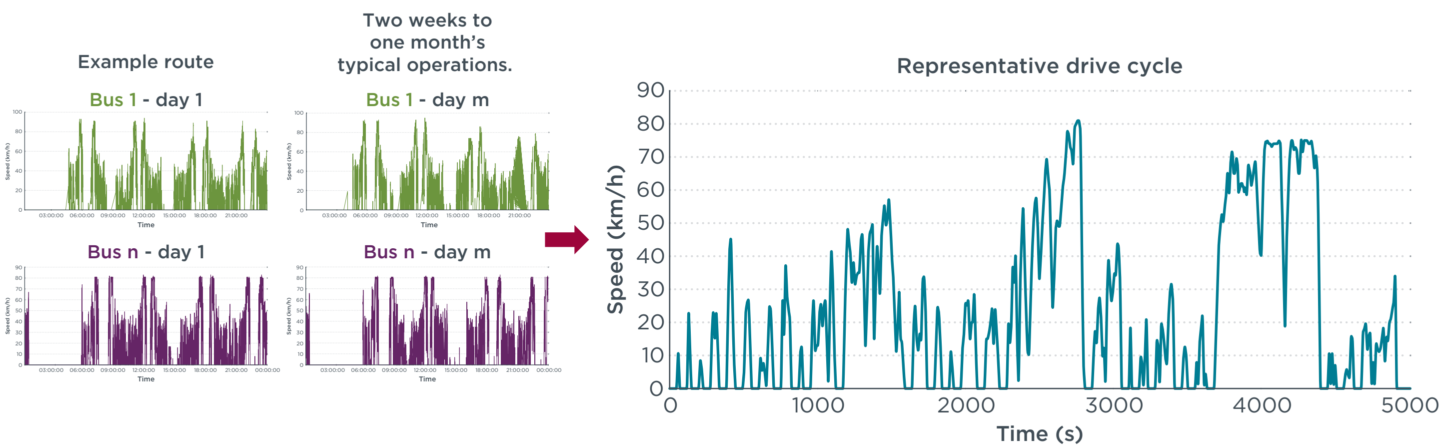


**Figure 2.** Illustration of a drive cycle developed for a route from real-world operational data

## Results and discussion

To demonstrate the development of drive cycles based on real-world data, we selected depots and routes which are described in BMTC's 2019 FAME-II proposal. We selected ten routes for energy validation and four routes for further analysis. These routes vary by route length, number of buses, and the number of trips run per day. The following section presents the outputs for individual routes.

## Drive cycle results

### *Characteristics of routes*

Four of routes described in the BMTC request for proposals were selected for analysis in this paper, the basic characteristics of which are shown in Table 2. These four routes range from 28.1km to 50km in length. Two routes, KIAS-7A and KIAS-12, are airport-bound routes. The V-356 route was selected in the final proposal for electrification, while V-335E was considered but not selected. These two routes run in different parts of the city. The number of buses/schedules range from four to 78 per route and make from 33 to over 600 total trips per route per day. Figure 3 shows the trip origin and destination of these routes in blue.

**Table 2.** Characteristics of four selected BMTC routes for drive cycle development

| Route number | Length (km) | Number of buses | Number of total trips per day |
|---|---|---|---|
| **KIAS-7A** | 50 | 4 | 33 |
| **KIAS-12** | 49 | 6 | 60 |
| **V-335E** | 28.1 | 78 | 632 |
| **V-356** | 29.2 | 15 | 129 |

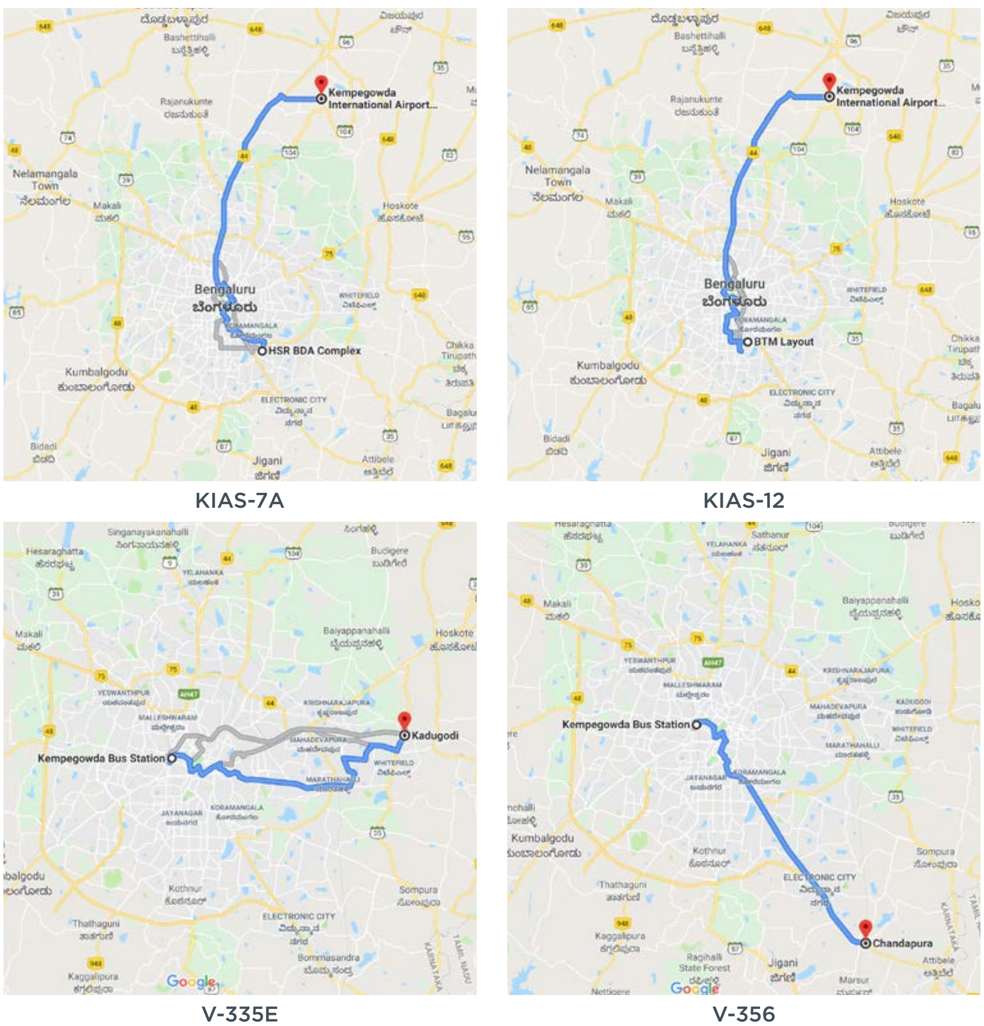


**Figure 3.** Maps of selected BMTC routes for drive cycle development. The routes are highlighted in blue. Source: Google maps

Table 3 shows the key metrics of the drive-cycles developed for these four routes. These drive cycle metrics are compared against their associated GPS data. This table gives a sense of the basic operational characteristics of the routes and their drive cycles. The drive cycle tool aims to minimize the RMS error of a selected group of metrics that are related to energy consumption. Drive cycle and GPS metrics are intended to be similar, but not necessarily match.

**Table 3.** Comparison of key metrics between drive-cycles and GPS-based data

| Route | Data type | Average speed (km/h) | Average driving speed (km/h) | Maximum speed (km/h) | Standard deviation of speed | Average stops per km |
|---|---|---|---|---|---|---|
| **KIAS-7A** | GPS | 20.8 | 34.6 | 120 | 24.3 | 0.4 |
| | Drive cycle | 27.3 | 34.1 | 79.9 | 24.7 | 0.6 |
| **KIAS-12** | GPS | 18.6 | 32.6 | 94.1 | 23.5 | 0.5 |
| | Drive cycle | 22.5 | 30.9 | 81 | 24.4 | 0.9 |
| **V-335E** | GPS | 9.6 | 21 | 110 | 14 | 1 |
| | Drive cycle | 16 | 21.3 | 58.4 | 15.2 | 1.1 |
| **V-356** | GPS | 10.7 | 23.6 | 95.6 | 16.2 | 0.9 |
| | Drive cycle | 18.2 | 22.6 | 68.9 | 18.2 | 0.8 |

### *Comparison to other drive cycles*

Table 4 compares the key metrics of each of the four BMTC drive cycles against other available bus drive cycles. The Santiago (TS-STGO), Braunschweig, Orange County Transit (US-OCTA), and Manhattan cycles are based on driving patterns in Santiago, Chile; Los Angeles, USA; Braunschweig, Germany; and New York City (Manhattan), USA, respectively. The Urban Dynamometer Driving Schedule (UDDS) was developed for chassis dynamometer testing of heavy-duty vehicles and is the basis for the FTP transient engine dynamometer cycle in the United States. Figures in the Appendix show the speed and time profiles of these cycles.[8]

**Table 4.** Comparison of key metrics between drive-cycles

| Cycle | Duration (s) | Distance (m) | Average speed (km/h) | Average driving speed (km/h) | Max speed (km/h) | Idle time | Average stops per km | Kinetic intensity ($km^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| **Santiago** | 1827 | 9977 | 19.7 | 24.2 | 73.6 | 19% | 2.6 | 2.5 |
| **Braunschweig** | 1740 | 10873 | 22.5 | 30.1 | 58.2 | 25% | 2.7 | 1.87 |
| **US-OCTA** | 1909 | 10526 | 19.8 | 25.2 | 65.4 | 21% | 2.9 | 2.23 |
| **Manhattan** | 1089 | 3325 | 11 | 17.2 | 40.9 | 36% | 6 | 5.67 |
| **UDDS** | 1060 | 8935 | 30.3 | 45.4 | 93.3 | 33% | 1.5 | 0.38 |
| **KIAS-7A** | 5184 | 39332 | 27.3 | 34.1 | 78.9 | 19% | 0.5 | 0.47 |
| **KIAS-12** | 5012 | 31332 | 22.5 | 30.9 | 81 | 27% | 0.9 | 0.48 |
| **V-335E** | 5657 | 25096 | 16 | 21.3 | 58.4 | 25% | 1.1 | 1.54 |
| **V-356** | 5543 | 28013 | 18.2 | 22.6 | 68.9 | 19% | 0.8 | 1.2 |

Some of these cycle metrics have been found to have a strong effect on fuel consumption, such as average speed, stops per km, percentage of idle time, and

8 .csv files showing the time, speed, and grade profiles of the four BMTC drive cycles are also available from the authors.

kinetic intensity (Tu et al., 2013). Kinetic intensity is a measure of drive cycle kinetics reflecting how much “stop and go” is in the cycle. This metric is derived from the ratio between characteristic acceleration and aerodynamic speed and measures the energy available for regeneration, which can help identify drive cycles where hybridization would offer fuel economy improvements (O’Keefe et al., 2007). Characteristic acceleration measures the inertial work to accelerate and/or raise the vehicle per unit mass per unit distance over the cycle. Aerodynamic speed measures the ratio of the average cubic speed to the average speed and characterizes the impact of aerodynamic resistance on vehicle fuel usage.

Since the minimum duration of the drive cycle is user-defined, for BMTC routes we set a value of one hour. This metric can be varied depending on testing or simulation constraints. The bus drive cycles shown in Table 4 are shorter than one hour to accommodate chassis dynamometer tests. Since we are not developing these drive cycles for a chassis dynamometer tests, we set a longer duration for the BMTC drive cycles.

Variation across bus drive cycles can reflect the type of route, bus schedule, and operator driving habits. The two BMTC airport drive cycles developed here, KIAS-7A and KIAS-12, have higher average and maximum speeds due to the fact they are longer routes that run to the Kempegowda International airport on the north side of the city in Bangalore Rural District. They also feature high-speed operation that is similar to the UDDS drive cycle. The BMTC V-335E and V-356 drive cycles are similar to the Santiago, Braunschweig, and US-OCTA drive cycles that represent typical urban bus driving patterns in congested cities. The Manhattan cycle is characterized by frequent stops and very low speed, based on driving patterns in highly-congested downtown New York City.

## Energy consumption evaluation

In order to validate the representativeness of the output of the cycle development tool, we compared output of the tool from one simulation, or “short” route, with the real-world cycle from the GPS data for a randomly selected day of operation of a bus over the given route, or “long route.” We based this comparison on the energy consumption of a commercially available electric bus (see Table 5 for bus parameters) over both the short and the long routes using Autonomie vehicle simulation software (Argonne National Laboratory, n.d.).

**Table 5.** Simulation parameters of the electric bus

| Bus technical parameter | Value |
|---|---|
| **Length (m)** | 12 |
| **Curb weight (kg)** | 13,100 |
| **Gross vehicle weight (kg)** | 18,000 |
| **Aerodynamic drag coefficient** | 0.65 |
| **Tire rolling resistance (N/N)** | 0.008 |
| **Wheel radius (m)** | 0.49 |
| **Electrical accessory power demand (kW)** | 6 |
| **Electric motor peak power (kW)** | 300 |
| **Battery capacity (kWh)** | 322 |

We selected an expanded set of ten routes for energy validation in addition to the four described above. Table 6 shows the energy consumption results for ten selected

BMTC routes. The energy consumption differences range between -6% and 15%, and the average absolute error is approximately 5%. As shown, the energy consumption of the short routes is a good representation of that of the long routes. Note that differences are expected, as the short route aims to represent the complete database, and the long route is only a subset of such database. Similarly, the median of a statistical distribution cannot be expected to exactly match the median of a subset of such distribution. Based on this exercise, we demonstrate that the drive cycles obtained from the operation data are representative of energy consumption within an acceptable margin of error.

**Table 6.** Comparison of energy consumption simulation for GPS data and drive cycle

| Route Type | Route number | Distance travelled (km) | Time (s) | Average speed (km/h) | Energy consumption (kWh/km) | Error |
|---|---|---|---|---|---|---|
| Long | KIAS-12 | 382.0 | 61503.9 | 22.4 | 1.216 | |
| Short | KIAS-12 | 37.5 | 6827.9 | 19.8 | 1.174 | -3% |
| Long | KIAS-6 | 108.8 | 52175.7 | 7.5 | 1.353 | |
| Short | KIAS-6 | 23.1 | 11002.2 | 7.6 | 1.554 | 15% |
| Long | KIAS-7A | 368.9 | 60219.7 | 22.1 | 1.270 | |
| Short | KIAS-7A | 39.8 | 6922.2 | 20.7 | 1.206 | -5% |
| Long | KIAS-8 | 379.4 | 66159.1 | 20.6 | 1.171 | |
| Short | KIAS-8 | 33.1 | 7944.3 | 15.0 | 1.177 | 0% |
| Long | KIAS-8E | 195.3 | 50034.4 | 14.0 | 1.211 | |
| Short | KIAS-8E | 34.4 | 9793.7 | 12.6 | 1.193 | -1% |
| Long | V-335E | 156.7 | 58229.8 | 9.7 | 1.238 | |
| Short | V-335E | 44.4 | 15707.7 | 10.2 | 1.231 | -1% |
| Long | V-356 | 190.7 | 26543.9 | 25.9 | 1.247 | |
| Short | V-356 | 31.5 | 10342.7 | 11.0 | 1.174 | -6% |
| Long | V-360B | 101.6 | 28608.0 | 12.8 | 1.219 | |
| Short | V-360B | 25.9 | 7952.6 | 11.7 | 1.275 | 5% |
| Long | V-500A | 174.3 | 39942.6 | 15.7 | 1.328 | |
| Short | V-500A | 20.0 | 7429.1 | 9.7 | 1.391 | 5% |
| Long | V-500D | 96.7 | 30581.8 | 11.4 | 1.220 | |
| Short | V-500D | 23.7 | 7611.2 | 11.2 | 1.348 | 11% |

## Conclusions

Fleet-wide planning supports the evaluation and selection of alternative vehicle technologies and infrastructure to be deployed in an urban bus fleet. Route-level total cost-of-ownership is one approach to fleet-wide planning. This paper presents the methods for development of representative drive cycles of urban bus fleet operations, the first step in a multi-step route-level TCO modeling framework. Routes currently operated by the Bangalore Metropolitan Transport Corporation were used to illustrate the application of a drive cycle development tool. The results of the tool for four BMTC routes were compared against other available drive cycles. In addition, Autonomic energy simulation software provided comparisons of the energy performance of a zero-emission bus along an expanded set of ten BMTC routes with their drive cycles. The results demonstrate that representative drive cycles developed from GPS data can reflect the energy consumption of different technologies along the original routes.

Further research can support the application of this methodology to a wider range of cities representing a wider range of driving conditions. Future work will demonstrate the additional steps in a route-level TCO framework required to estimate route-level emissions and costs when coupled with route-level drive cycle development. Together, this framework aims to support technology selection and operational planning to accelerate the transition to soot-free, low-carbon, and zero-emission vehicles.

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## Appendix

The figures below show the time and speed profiles of the drive cycles shown in Table 4. Data showing time, speed, and grade profiles of the four BMTC drive cycles are available from the authors.

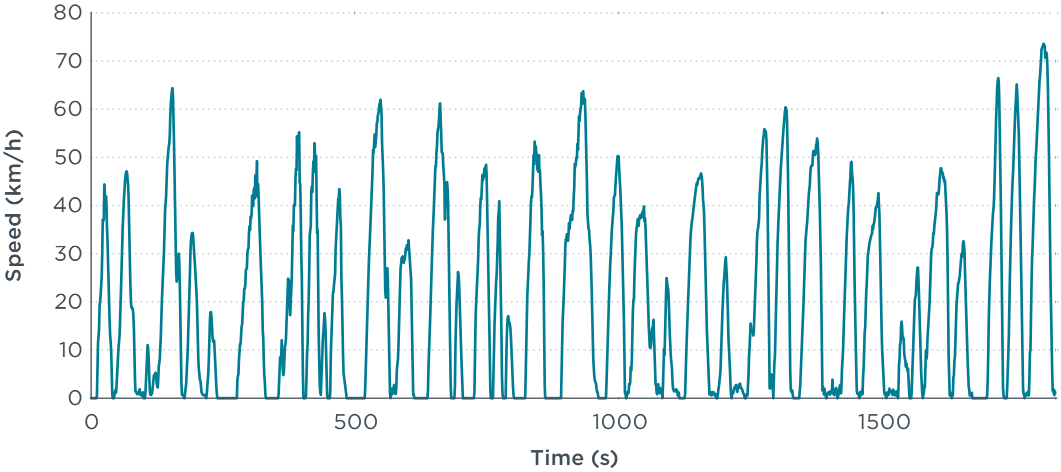


**Figure A1.** Santiago (TS-STGO) cycle speed vs. time

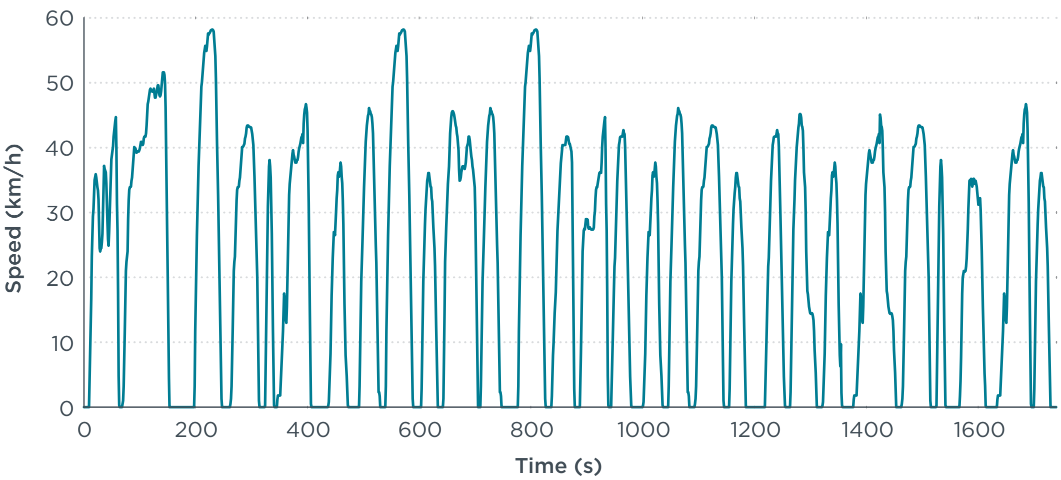


**Figure A2.** Braunschweig cycle speed vs. time. Data from Dieselnet (2013)

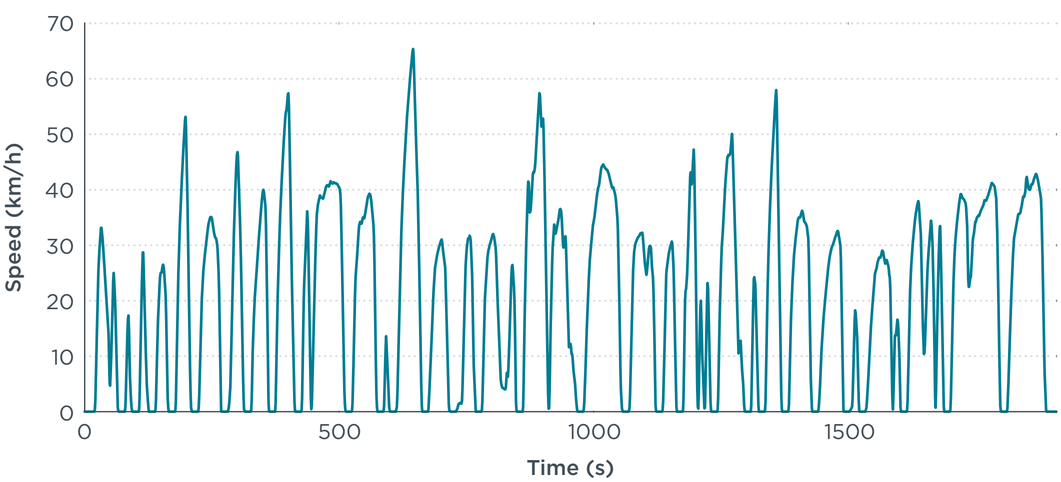


**Figure A3.** Orange county transit bus cycle (US-OCTA) speed vs. time. Data from Dieselnet (2002)

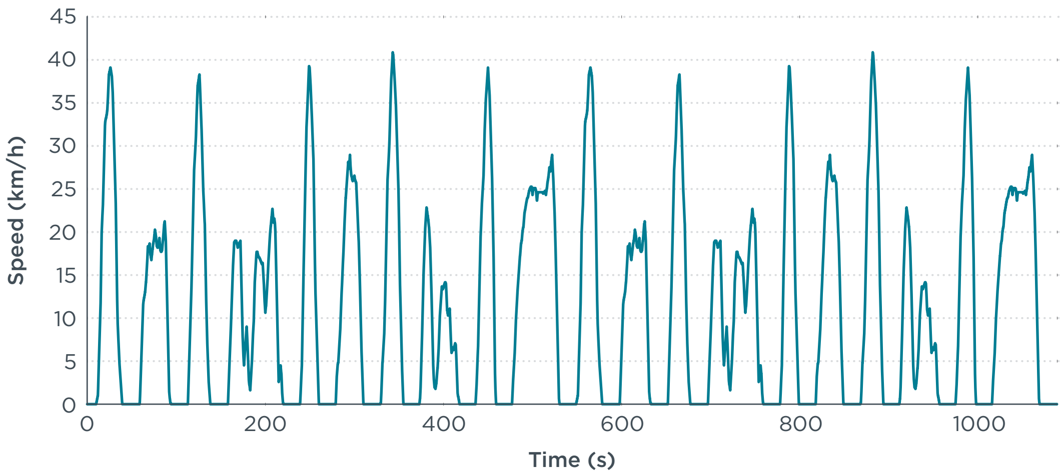


**Figure A4.** Manhattan cycle speed vs. time. Data from Dieselnet (2003)

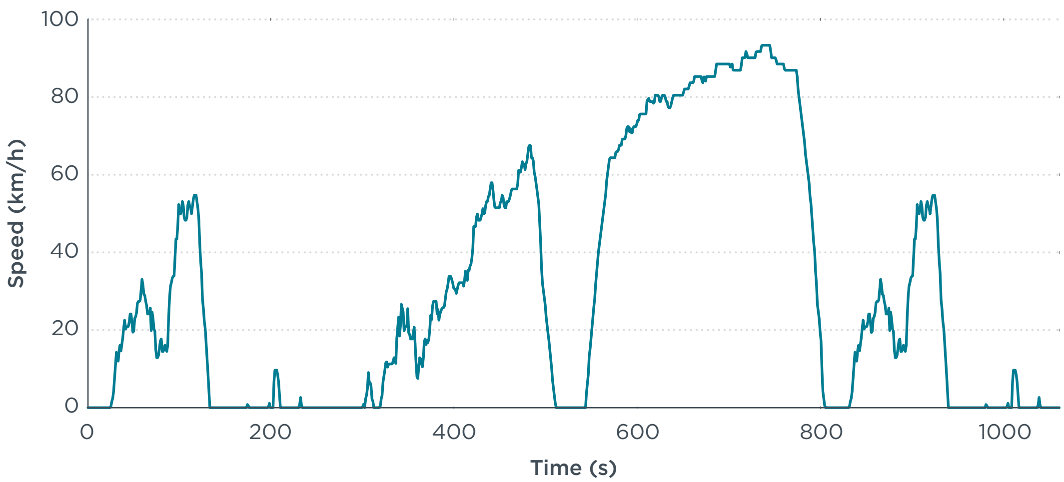


**Figure A5.** UDDS cycle speed vs. time

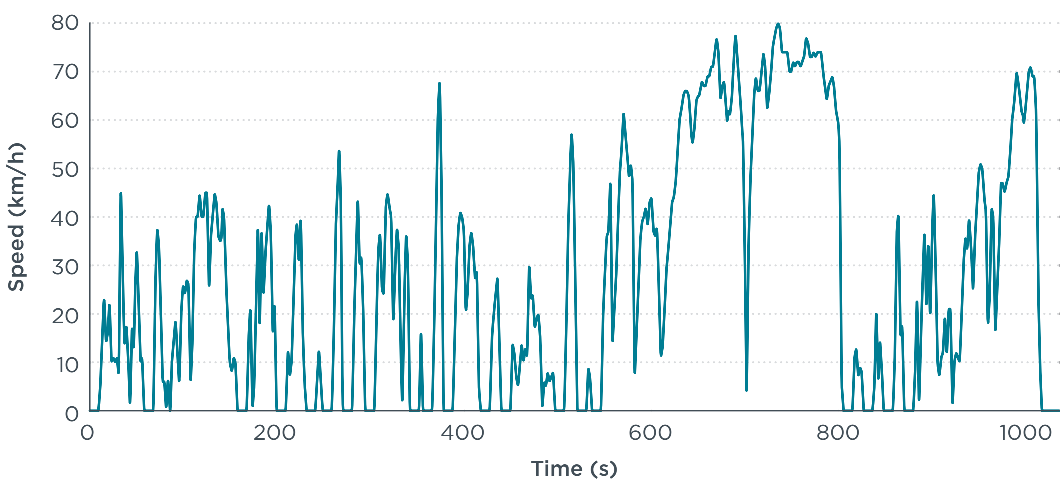


**Figure A6.** Bangalore KIAS-7A drive cycle speed vs. time

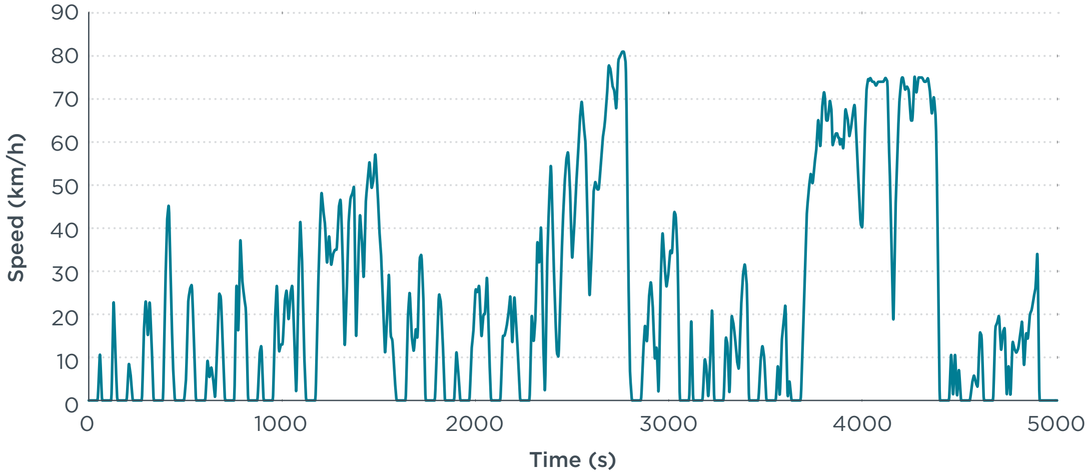

**Figure A7.** Bangalore KIAS-12 drive cycle speed vs. time

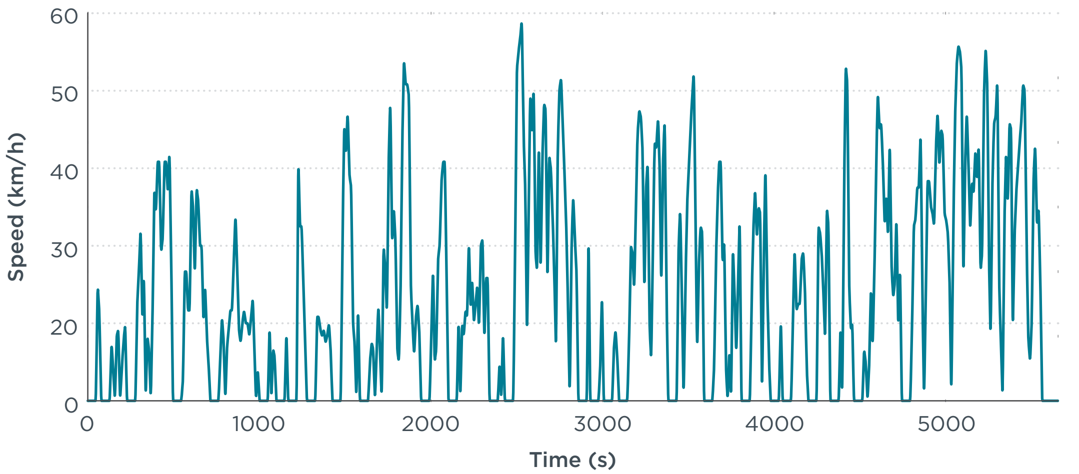

**Figure A8.** Bangalore V-335E drive cycle speed vs. time

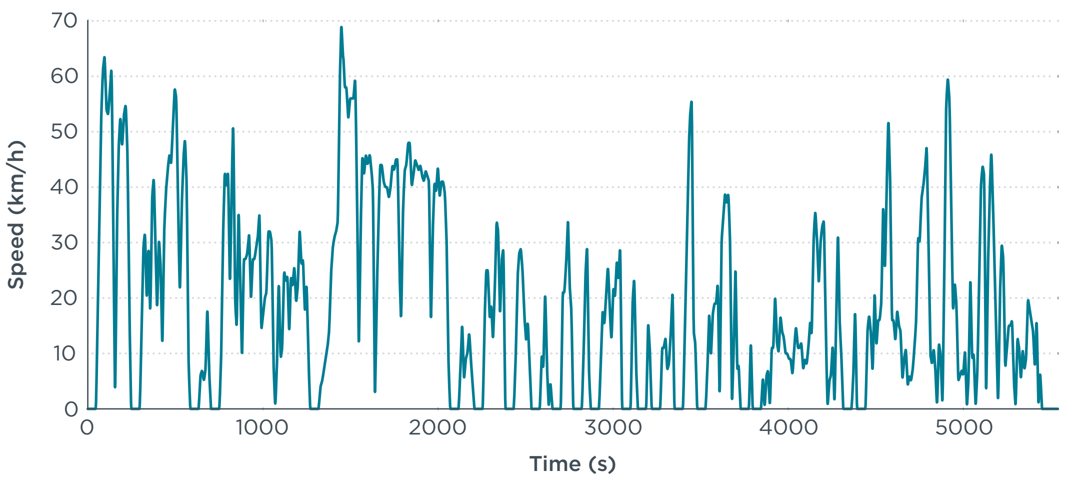

**Figure A9,** Bangalore V-356 drive cycle speed vs. time

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