Texas A&M Transportation Institute

Application of Wejo Data for Texas-Specific Drive Cycle Development and Emissions Impacts

Final Report

Prepared for the Texas Department of Transportation (TxDOT)

July 2024

Texas A&M Transportation Institute

Grant No:

Sub-Task 3.1 – Final Report

DATE: July 26, 2024

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LIST OF ACRONYMS

- **CNG**: Compressed Natural Gas
- **CO**: Carbon Monoxide
- **CO_2**: Carbon Dioxide
- **CV**: Connected Vehicles
- **DFW**: Dallas and Fort Worth
- **HCM**: Highway Capacity Manual
- **HPMS**: Highway Performance Monitoring System
- **LDV**: Light Duty Vehicles
- **LOS**: Level of Service
- **MOVES**: Motor Vehicle Emission Simulator
- **NOx**: Oxides of Nitrogen
- **PM**: Particulate Matter
- **SIP**: State Implementation Plan
- **SUV**: Sports Utility Vehicle
- **TxDOT**: Texas Department of Transportation
- **VMT**: Vehicle Miles Traveled
- **VOC**: Volatile Organic Compounds
- **VSP**: Vehicle-Specific Power

EXECUTIVE SUMMARY

Drive cycles can affect emissions noticeably and vary by geographical location. The default drive cycles in MOVES were developed based on data from a few major cities along the East and West Coast, with all datasets collected before 2005. To assess the emission estimation accuracy, the main objective of this work was to develop drive cycles that best represent the driving conditions in Texas using the Wejo data. The Wejo data consists of most of the urban trips taken by light-duty vehicles. The trips were classified into various drive cycle categories based on area types (urban/rural), road types(arterial/freeways), and average speed. In total, 17 drive cycles were developed using the following steps: Firstly, the trips were mapped to MOVES road types and, in the case of freeways, the desired parts of the trips were extracted. Secondly, the operating mode distribution of individual trips is calculated. A universal operating mode distribution for each drive cycle category was calculated by concatenating the distributions of all the trips in that category. Lastly, the trip having the operating mode distribution closest to the universal distribution was selected as a drive cycle. The developed drive cycles have significantly different operating mode distributions as compared to the MOVES defaults.

The developed drive cycles were further integrated with MOVES simulation for light-duty vehicles and urban road types. Two simulations were performed, one using MOVES default drive cycles and one using Texas-specific drive cycles. As an example, Dallas County was chosen and monthly emissions were calculated for important pollutants including $PM_{2.5}$, PM_{10}, oxides of nitrogen (NOx) and volatile organic compounds (VOCs). In general, the emissions using Texas-specific drive cycles were higher for urban arterials and lower for urban freeways. CO shows the highest increase of 5.62% in overall emissions from LDVs by using Texas-specific drive cycles. For NOx and VOCs, the overall difference in emissions was less than 1%. However, for $PM_{2.5}$ and PM_{10} the emissions were 2.90% and 2.97% higher using Texas-specific drive cycles respectively. These differences could be important, considering the non-attainment of the considered area.

The developed drive cycles are based on operating mode distributions of thousands of trips and capture local driving conditions. The report demonstrates that the Wejo data can be used for drive cycle development.

1 INTRODUCTION

The EPA's official emission model is the Motor Vehicle Emission Simulator (MOVES). It calculates emissions for mobile sources, providing default parameters as well as capability of custom input parameters for county and project-level to estimate for criteria air pollutants, greenhouse gases, and air toxics. MOVES4 (1), released in September 2023, is the latest version of EPA's MOVES emission model (MOVES4) that replaced the previous version, MOVES3. Compared to MOVES3, MOVES4 incorporated changes and updates in vehicle populations, fuel supply, travel activity, and emissions rates (2). MOVES4 also enhanced its capability to model light-duty electric vehicles, heavy-duty battery electric and fuel-cell vehicles, and compressed natural gas (CNG) long-haul combination trucks. However, both versions use only the national average driving schedules (also called drive cycles or driving cycles) in the default database of the model. In this analysis, MOVES4.0.1 was used and hereafter is referred to as MOVES.

Macroscopic emissions modeling in MOVES model uses such drive cycles, as shown in Figure 1, to transform instantaneous emissions into emissions rates. Thus, driving cycles not only affect the accuracy of emissions estimates but also provide a means of translating emissions from the microscopic level to the macroscopic level. At the microscopic level, second-by-second basis emissions are obtained through drive cycles. At the macroscopic level, total emissions are estimated by combining data related to individual vehicular emissions with various driving conditions as captured by the drive cycle. Because these drive cycles provide a means of translating microscopic-level vehicle activity to macroscopic level modeling, they are an important aspect of the emissions estimation process and must therefore reflect to the highest degree possible the actual driving conditions within the area being studied. This is particularly true for state and local air quality, and for transportation agencies that are required to estimate on-road vehicle emissions for various purposes including demonstrating progress toward attainment, maintaining state implementation plans, and regional transportation planning.

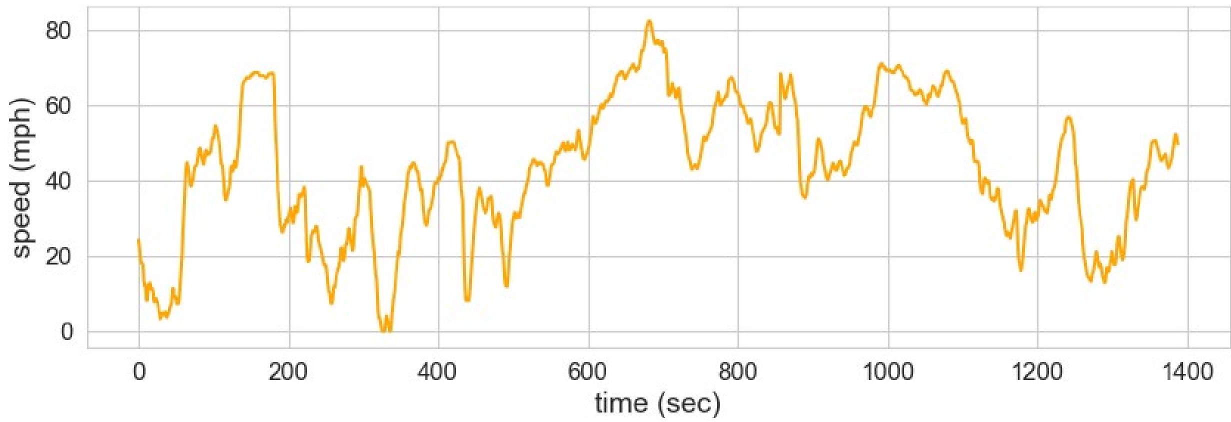


Figure 1. Drive cycle example

Drive cycles can affect the emissions noticeably and vary by geographical location. The default drive cycles in MOVES were developed based on data from a few major cities along the East and West Coast, with all datasets collected before 2005. Thus, there is a need to develop Texas-specific drive cycles to reflect traffic activities in Texas to improve emission estimation accuracy. Accurate emission estimates based on local and recent drive cycles are essential for understanding regional air quality and near-road communities' health impacts, developing effective countermeasures, and ensuring transportation projects are not unduly impacted due to less accurate environmental analysis.

Previously, instrumental vehicles or the chase car method were traditionally used to collect this data. However, recently probe data, which enable communication at close to one Hertz frequency from sources such as connected vehicles (CVs) or mobile phones is readily available. Probe data provided by Wejo (3) can be readily used with some processing for developing customized drive cycles for different Texas regions for specific vehicle types. Additionally, the probe data has broader temporal and spatial coverage than the data collected traditionally and thus can provide customized drive cycles for various periods and regions.

The main objective of this study is to provide TxDOT with localized drive cycles for Texas using Wejo probe data. The emissions from MOVES using Texas-specific drive cycles are compared with the emissions using default drive cycles and highlighted in this memo.

2 LITERATURE REVIEW

2.1 DRIVE CYCLE DEFINITION AND IMPACT ON EMISSION MODELING

Drive cycle refers to a second-by-second vehicle speed trajectory over time. Drive cycles in MOVES are intended to include all vehicle operations from the time the engine starts until the engine is keyed off, both driving (travel) and idling time. Drive schedules are used in MOVES to determine the operating mode distribution for MOVES running processes for calculation of emissions and energy consumption. MOVES4 and MOVES3 use identical drive cycles. The drive schedules in MOVES3 are unchanged from those in MOVES2014, except for additional drive schedules for transit and school buses.

A key feature of MOVES is the capability to accommodate many drive cycles to represent driving patterns across source type, road type, and average speed. For the national default case, MOVES uses 49 drive schedules to represent various average speeds, different source types and road types. MOVES stores all drive cycle information in three database tables. The "DriveSchedule" table provides the drive cycle name, identification number, and the average speed of the drive cycle. The "DriveScheduleSecond" table contains the second-by-second vehicle trajectories for each cycle. The "DriveScheduleAssoc" table links drive cycles to MOVES road types.

MOVES uses different algorithms to calculate emissions for various processes like running, idling and hotelling. An example of emission calculation for running exhaust is given below in Figure 2. An example is demonstrated to display the significance of drive cycles and operating modes in emissions calculations. For the detailed algorithms of other processes, please refer to the Overview of MOVES3 document (4).

Running emissions are the archetypal mobile source emissions which includes exhaust emissions from a running vehicle. Running operation is defined as an operation of internal-combustion engines after the engine (or motor) and emission control systems have stabilized at operating temperature, i.e., "hot-stabilized" operation (4). The general flow of information to calculate running emissions for onroad sources is summarized in Figure 2. The model uses vehicle population information to categorize the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year, and age. For each source bin, the model uses vehicle characteristics and activity data like vehicle miles traveled (VMT), speed, idling fractions, and driving cycles to estimate the source hours in each running operating mode. The running operating modes are defined by the vehicle's instantaneous speed, acceleration and estimated vehicle-specific power (VSP). Each source bin and operating mode is associated with an emission rate, and these are multiplied by source hours, adjusted as needed, and summed to estimate the total running emissions. MOVES may adjust the running emissions to account for local fuel parameters, meteorological conditions, inspection and maintenance programs, and fuel economy adjustments.

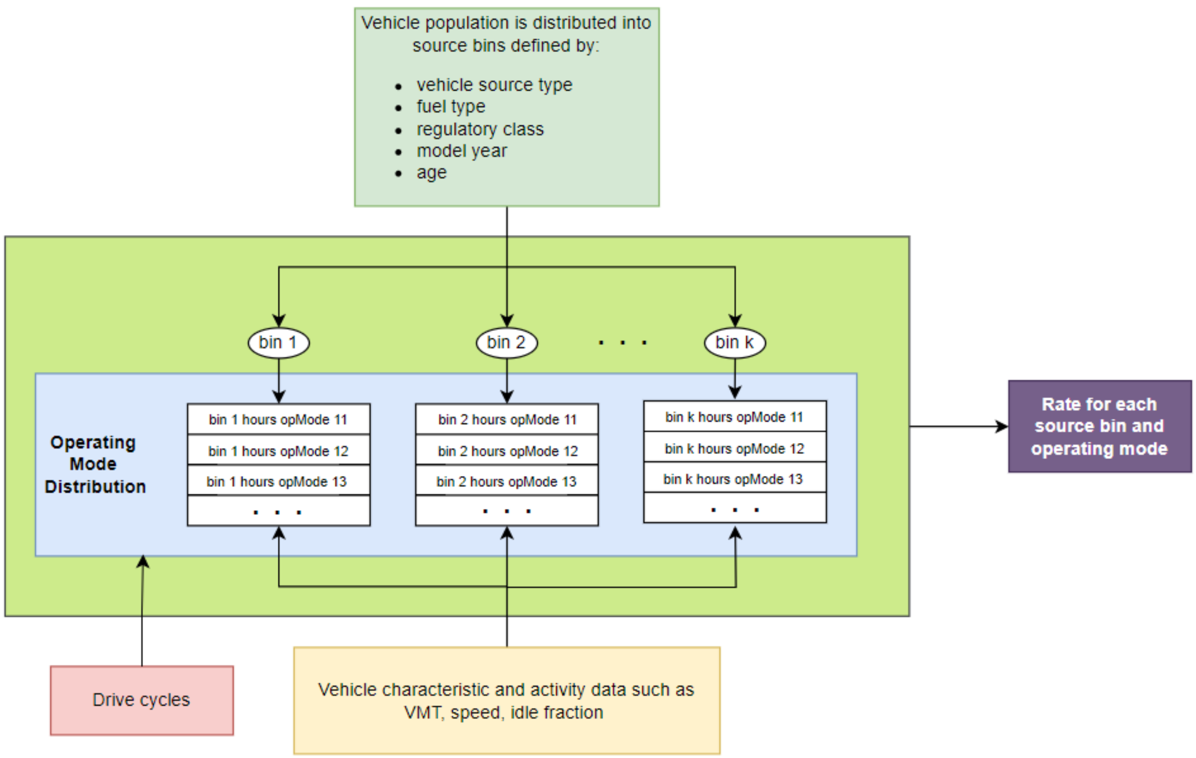


Figure 2. Drive cycles to calculate emissions

2.2 MOVES DRIVE CYCLES

MOVES uses 49 drive cycles to model the microscopic characteristics of trips by different average speed, different vehicle type, and different road type. These drive cycles provide the requisite data for estimating trip emission rates. The 49 default MOVES drive cycles were all developed based on data collected before 2005. Table 1 provides the sources and metadata on the data collection studies for the 49 default MOVES drive cycle. MOVES is still using some drive cycles dating back to 1990. It should be reasonable to assume that over the last 19 to 34 years, vehicle, road, and driver characteristics would have changed.

Table 1 Moves default drive cycles

Drive Schedule ID	Number of Drive Cycles	Year	Location	Number of Vehicles	Vehicle Types	Method	Reference
101	1	Historic (likely pre-1990*)	Unknown	Unknown	Light-Duty	Unknown	(5)
153, 355, 396, 397	4	1992*	Spokane, Washington; Baltimore, Maryland; Atlanta, Georgia; and Los Angeles, California.	>300	Light-Duty	Instrumented vehicle (Data loggers) and chase car	(6,7)
158	1	2001	Ann Arbor, Michigan	18	Light-Duty	Instrumented vehicles	(8,9)
402, 403	2	2001	Ann Arbor, Michigan	17	Diesel Buses	Instrumented vehicles	(8,9)
401, 404	2	Historic (likely pre-1990*)	Not Applicable (N/A)	Unknown	New York City Transit Bus	Chasis Dynamometer Test	(5,10,11)
398	1	2005*	N/A	20		Chasis Dynamometer Test	(12)
405	1	2003*	N/A	12	WMATA Transit Buses	Chasis Dynamometer Test	(13)
1000–1999	15	2000	Sacramento metropolitan area, San Francisco Bay Area, Stanislaus County (including Modesto metropolitan area), and South Coast (Los Angeles) in California	Unknown		Instrumented vehicle	(14)
200–355	21	2003*	Austin, TX, Columbus, OH, and Unknown	254	Medium Duty, Heavy Duty, and 4 Refuse Trucks from Austin, TX	GPS Measurement	(15)
501	1	2005*	N/A	10	Caterpillar C-10 Engine Refuse Trucks	Chasis Dynamometer Test	(16)

*For these studies, the year denotes the year of the report, not the data collection. The data collection is earlier than the year listed.

Moreover, the data were primarily collected in major East and West Coast cities, except for four dump truck data collected from Austin, Texas. Figure 3 shows the study locations of the 49 MOVES default drive cycle. MOVES uses factors for longer idling due to off-network idling at locations such as parking lots and drive-throughs. However, the underlying drive cycles were not updated.

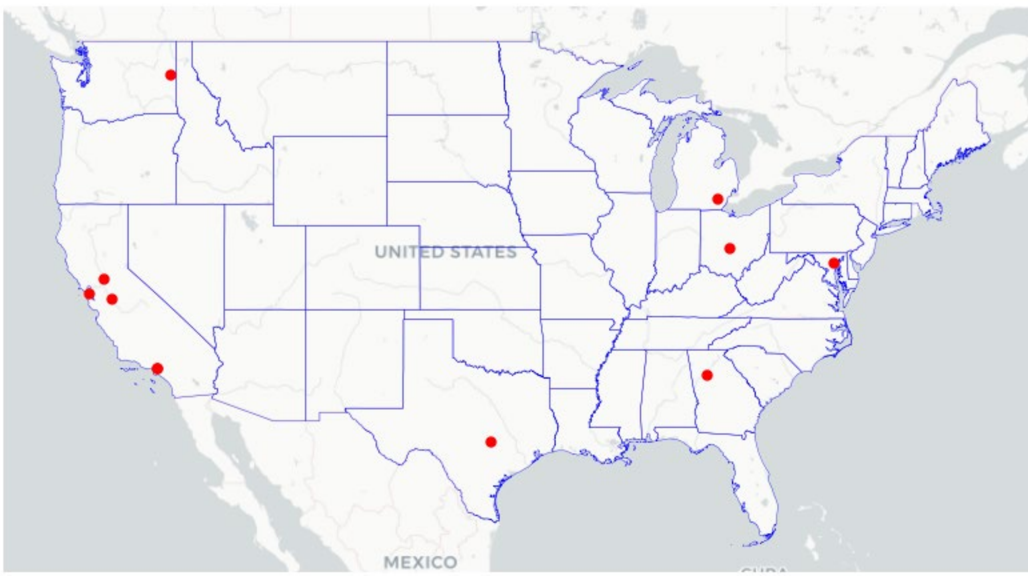


Figure 3 Location for MOVES drive cycle studies

Apart from the biased spatial sampling and dated data, the drive cycles have another important issue that arises from using a limited number of drive cycles to cover 832 groups formed by 13 MOVES source use types, four MOVES road types, and 16 MOVES average speed bins. Due to the limited number of drive cycles, some drive cycles are used for incongruous categories. For instance, the "Final FC11LOSF" (2009 FHWA functional class 11: Urban Interstate and highway capacity manual [HCM] Level of Service [LOS] F) cycle was developed for Urban Interstate (14) but is used for unrestricted access (5). Arterials, collectors, or local streets (unrestricted access roads) likely have different characteristics at LOS F compared to a freeway, such as vehicles entering and leaving from driveways along the arterial or traffic signal cycle failures due to demand exceeding capacity. Also, HCM uses different definitions for determining LOS for freeways (density) and intersections (delay) (17), so the LOS definition of one road type does not apply to another. The bus drive cycles from Ann Arbor, Michigan, New

York City, and Washington, D.C. are for a completely different geography than Texas and might have very different route characteristics.

Given that the data used for default drive cycles are dated, not developed for Texas driving characteristics, and do not comprehensively cover the various macroscopic categories based on source use types, average speeds, and road types that require drive cycles, there is a need for an update. Another limitation of previous studies is that they often needed to collect data, which required time, funding, and resources. With the recent advances in CV technology and CV data vendors such as Wejo, it is possible to easily access and utilize the trajectory data for millions of trips for drive cycle development. The next section showcases the drive cycle-related information in the Wejo data.

2.3 Overview of Wejo Data

We analyzed one week of Wejo data from September 18, 2022, to September 24, 2022, for 11 counties in Dallas and Fort Worth region (DFW area)[1]. The selected Wejo data has information for 11 million (11,768,979) trips. A journey consists of trajectory points typically read at one Hz frequency (one second) defined between engine on and off. The dataset includes the timestamp (date and time) which the data was recorded, latitude and longitude, speed, heading, and vehicle class identifier. It is important to notice that the vehicle class identifier does not identify one particular vehicle, but a class of which the vehicle belongs (e.g., pickup, SUV, sedan, hatchback, truck, minivan).

The vehicle activity during the collected data period is shown in Figure 3 for resolution 10 H3 grids[2]. The highest frequency of data records is in and around the cities of Dallas and Fort Worth counting more than 1,000,000 of captured signals at the highest.

[1] Collin, Dallas, Denton, Ellis, Hunt, Johnson, Kaufman, Parker, Rockwall, Tarrant, Wise counties.

[2] Resolution 10 H3 cells have an area of around 0.05 km^2 (18). "H3 is a geospatial indexing system that partitions the world into hexagonal cells. H3 is open source under the Apache 2 license." (19)

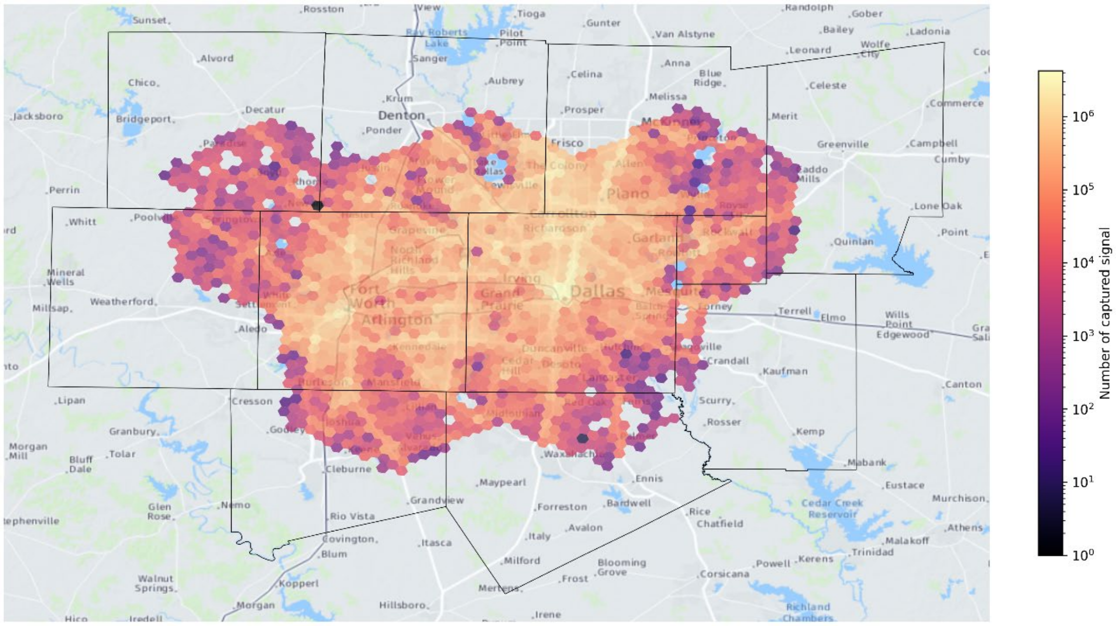


Figure 4. Number of captured signals in Wejo data for Dallas-Fort Worth region during September 18 to September 24, 2022.

3 DRIVE CYCLE DEVELOPMENT

3.1 Texas-specific Drive Cycle Development

Figure 5 gives an overview of the methodology used to develop Texas-specific drive cycles. The TTI research team selected trips with 1 second resolution from the Wejo data since those are the most suitable trips to develop drive cycles. Next the trips were divided into 34 categories, based on area (rural/urban), MOVES road type (freeways/arterials), and average trip speed. MOVES classifies road types as restricted access and un-restricted access. In this work, restricted access roads are referred to as freeways and unrestricted access roads are referred to as arterials. For example, category U_F_60 represents urban freeway trips with an average speed between 55 mph to 65 mph. From the trips in each category, a 'universal' operating mode distribution was developed for each category. Finally, a trip that has the closest operating mode distribution to the universal operating mode distribution was selected as a representative drive cycle for each category.

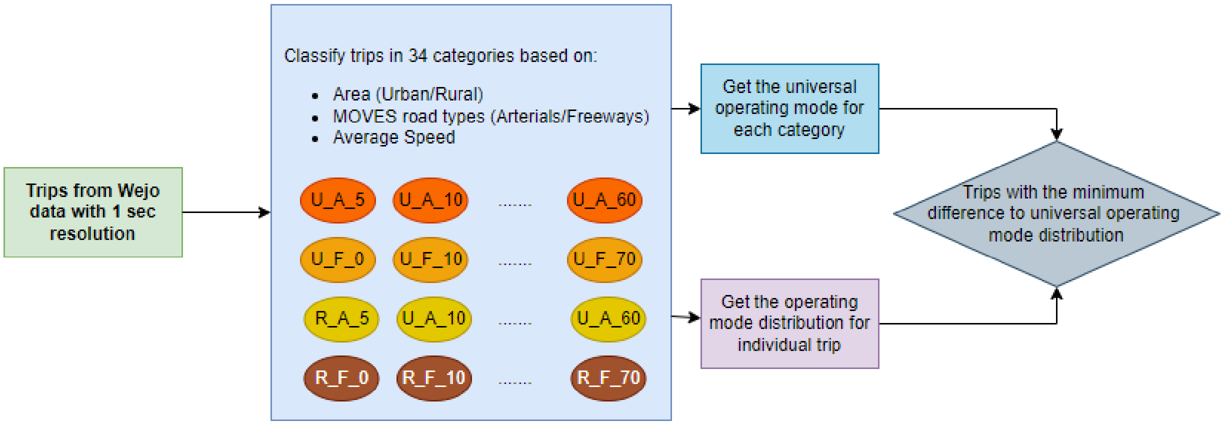


Figure 5. Overview of drive cycle development

This section describes the details of the steps that were used to develop Texas-specific drive cycles.

3.1.1 Extraction of trips from Wejo data

A Wejo trip data contains parameters such as vehicle coordinates (latitude and longitude), and speed at every second. During the extraction process, the research team first matched each position of a trip with the TxDOT roadway inventory to embed the highway performance monitoring system (HPMS) road functional classification system into Wejo data. This classification categorizes the roads in urban and rural and road functions such as interstate, arterials, collectors, and locals. The road functional classification system was used later for grouping the trips based on MOVES road types (see Table 2). After embedding the road classification system in Wejo data, the latitude and longitude columns were removed, and the data exported for further analysis. This last step was essential to keep the data private and avoid tracking one particular trip. The one second of time interval was used since those are the finest time resolutions of Wejo trip data, and detailed enough to represent drive cycles. Most of the data was available for light-duty vehicles (LDV). Hence, the study team focused on developing drive cycles only for LDVs.

Table 2. MOVES road types

Road type ID	MOVES road type	HPMS functional type
1	Off-network	Off Network
2	Rural restricted access	Rural Interstate
3	Rural unrestricted access	Rural Principal Arterial, Minor Arterial, Major Collector, Minor Collector, and Local
4	Urban restricted access	Urban Interstate and Urban Freeway/Expressway
5	Urban unrestricted access	Urban Principal Arterial, Minor Arterial, Collector, and Local

3.1.2 Classification of trips into drive cycle categories

After mapping the data points of trips with MOVES road types, the next step was to classify the trips based on area type and road type and average speed. Table 2 shows the categories for arterials and freeways. Different approaches were used to define the trips either as arterials or freeways. There were a sufficient number of trips where most of the data points of the trip lie on arterials. Hence, the research team used the following criteria to determine urban or rural arterial trips:

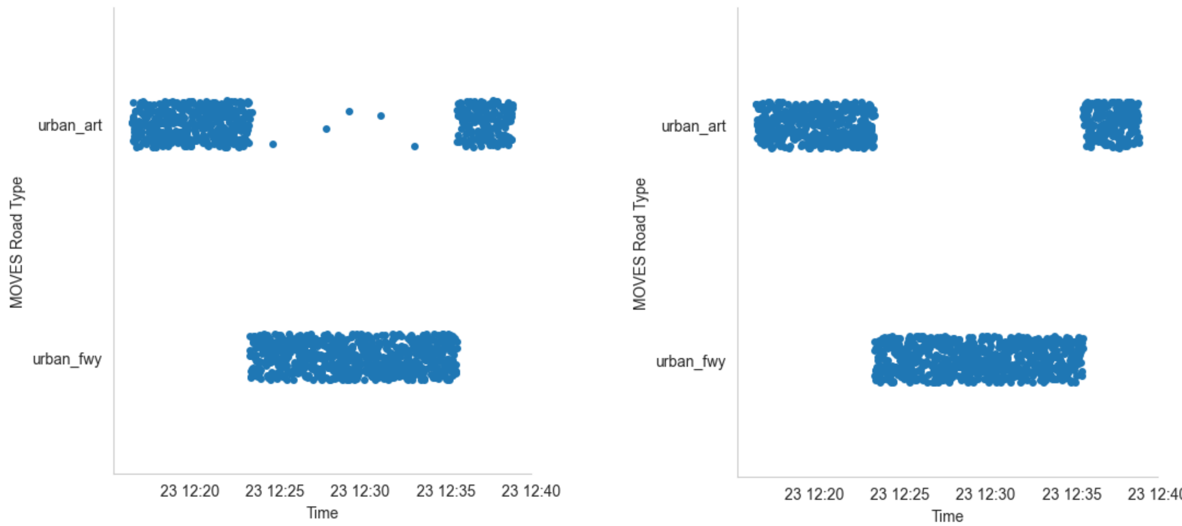
- U_A_X: More than 95% of the data points should lie on urban arterial and the average speed satisfies the conditions for speed bin category X.
- R_A_X: More than 95% of the data points should lie on rural arterial and the average speed satisfies the conditions for speed bin category X.

An example of a freeway trip is shown in Figure 6. Since most of the trips were on arterials before entering a freeway, and it is unlikely that a trip will start on a freeway, the research team used the following steps to determine urban or rural freeway trips:

- Trips with more than 50% points were considered for urban freeways. The same threshold was used for rural freeways.
- As shown in Figure 6 (a), there were some points which got classified on urban arterials during the urban freeway stretch of the trip. This may happen because

of the errors in the measurements. Moving average smoothening was applied on the road types to get a smoothened curve as shown in Figure 6 (b).

- After smoothening, only the part of the trip that is on a freeway was extracted.
- The average speed of the freeway part of the trips is used for the classification in the drive cycle categories shown in Table 3.



(a) Before smoothening (b) After smoothening

Figure 6. Example of a freeway trip

Table 3 illustrates all combinations of trip classification in this study.

Table 3. Drive cycle categories (20)

Roadway Types	Cases	Average speed bin (mph)	Speed bin definition based on average speed (u_{avg})
Arterials (Both rural and urban)	A_5	5	$0 \le u_{avg} < 7.5$
	A_10	10	$7.5 \le u_{avg} < 12.5$
	A_15	15	$12.5 \le u_{avg} < 17.5$
	A_20	20	$17.5 \le u_{avg} < 22.5$
	A_25	25	$22.5 \le u_{avg} < 27.5$
	A_30	30	$27.5 \le u_{avg} < 35$
	A_40	40	$35 \le u_{avg} < 45$
	A_50	50	$45 \le u_{avg} < 55$
	A_60	60	$55 \le u_{avg}$
Freeways (Both rural and urban)	F_0	2.5	$0 \le u_{avg} < 5$
	F_10	10	$5 \le u_{avg} < 15$
	F_20	20	$15 \le u_{avg} < 25$
	F_30	30	$25 \le u_{avg} < 35$
	F_40	40	$35 \le u_{avg} < 45$
	F_50	50	$45 \le u_{avg} < 55$
	F_60	60	$55 \le u_{avg} < 65$
	F_70	70	$65 \le u_{avg}$

Table 4 shows the number of trips in each of the drive cycle categories. The number of trips in urban areas are considerably higher as compared to the rural areas. Hence the research team decided to develop drive cycles only for the urban areas. On urban arterials, the majority of trips are for speed bins 5, 10, 15, 20, 25, and 30. On the other hand, the majority of speeds on freeways have average speeds in bins 50, 60, and 70. Though the number of trips is less for the U_A_50 and U_A_60 categories, the resaerch team still considered those trips to include all the speed bins.

Table 4 Number of trips in each drive cycle category

Category	# trips	Category	# trips	Category	# trips	Category	# trips
U_A_5	3384	U_F_0	27	R_A_5	19	R_F_0	0
U_A_10	3805	U_F_10	20	R_A_10	16	R_F_10	0
U_A_15	4936	U_F_20	92	R_A_15	24	R_F_20	0
U_A_20	4598	U_F_30	231	R_A_20	26	R_F_30	0

Category	# trips	Category	# trips	Category	# trips	Category	# trips
U_A_25	2805	U_F_40	412	R_A_25	10	R_F_40	0
U_A_30	1195	U_F_50	535	R_A_30	16	R_F_50	0
U_A_40	179	U_F_60	975	R_A_40	17	R_F_60	0
U_A_50	13	U_F_70	1890	R_A_50	10	R_F_70	7
U_A_60	3			R_A_60	1		

3.1.3 Operating mode distribution

This section explains the computation of operating modes. The operating mode is a function of VSP, speed, and acceleration. For running processes, there are 23 operating modes listed in Table 5 (21). Equation 1 shows the computation of VSP. Using VSP, speed, and acceleration, the operating mode for each time instant of the trip can be determined. In this way, the operating mode distribution of individual trips can be calculated.

$$VSP = \frac{Au + Bu^2 + Cu^3 + Mua}{M}$$ **Equation 1**

Where A, B and C are rolling, rotating and drag parameters, M is the source mass, u is the instantaneous speed, and a is the instantaneous acceleration. In this study, we used A = 0.156461, B = 0.002002, C = 0.000493 and M = 1.4788. These parameters were adopted from the previous study done by TTI in 2014 (20).

Table 5 Operating mode distribution (20)

Operating Mode ID	Operating Mode Description	VSP (kW/Ton)	Vehicle Speed (u, mph)	Vehicle Acceleration (a, mph/sec)
0	Deceleration/Braking			$a_t \leq -2.0$ OR ($a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$)
1	Idle		$-1 \leq u < 1$	
11	Coast	$VSP < 0$	$0 \leq u < 25$	
12	Cruise/Acceleration	$0 \leq VSP < 3$	$0 \leq u < 25$	
13	Cruise/Acceleration	$3 \leq VSP < 6$	$0 \leq u < 25$	

Operating Mode ID	Operating Mode Description	VSP (kW/Ton)	Vehicle Speed (u, mph)	Vehicle Acceleration (a, mph/sec)
14	Cruise/Acceleration	6≤VSP<9	0≤u<25	
15	Cruise/Acceleration	9≤VSP<12	0≤u<25	
16	Cruise/Acceleration	12≤VSP<3	0≤u<25	
21	Coast	VSP<0	25≤u<50	
22	Cruise/Acceleration	0≤VSP<3	25≤u<50	
23	Cruise/Acceleration	3≤VSP<6	25≤u<50	
24	Cruise/Acceleration	6≤VSP<9	25≤u<50	
25	Cruise/Acceleration	9≤VSP<12	25≤u<50	
27	Cruise/Acceleration	12≤VSP<18	25≤u<50	
28	Cruise/Acceleration	18≤VSP<24	25≤u<50	
29	Cruise/Acceleration	24≤VSP<30	25≤u<50	
30	Cruise/Acceleration	30≤VSP	25≤u<50	
33	Cruise/Acceleration	VSP<6	50≤u	
35	Cruise/Acceleration	6≤VSP<12	50≤u	
37	Cruise/Acceleration	12≤VSP<18	50≤u	
38	Cruise/Acceleration	18≤VSP<24	50≤u	
39	Cruise/Acceleration	24≤VSP<30	50≤u	
40	Cruise/Acceleration	30≤VSP	50≤u	

Similarly, a universal operating mode distribution was developed for a category by concatenating all the trips in that category. The performance metric for trip k,

$$Z(k) = \sum_{i=0}^{n} |{d_i}^t(c) \ - d_i(k)\,| \qquad \textbf{Equation 2}$$

Where i denotes operating mode, ${d_i}^t(c)$ is the density of the operating mode i in the universal distribution for category c, d_i is the density of the operating mode i. The trip with the minimum Z was selected as the representative drive cycle for each drive cycle category. The target distribution for the drive cycle category c, ${d_i}^t(c)$, was obtained by concatenating the operating mode distribution of all the trips in the drive cycle category c.

Table 6 lists the details of the developed drive cycles in each category. There is a large variation in the duration of developed drive cycles. However, all the drive cycle durations are acceptable. In MOVES default drive cycles, the duration ranges from 265 sec to over

5000 sec. Each Texas-specific drive cycle was assigned a specific drive-schedule ID which is further used to incorporate it with the MOVES simulation.

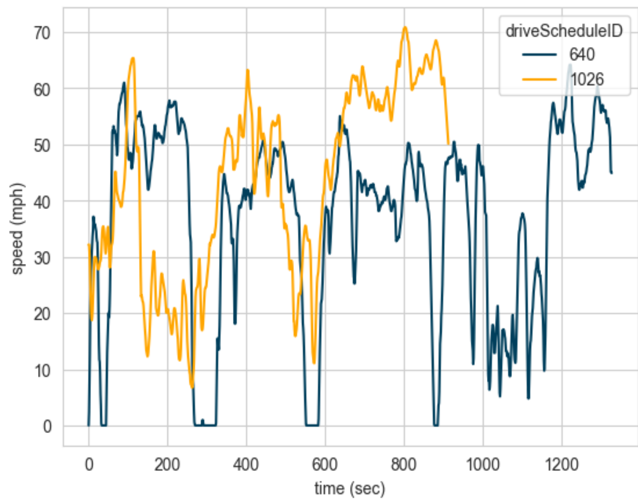
Table 6 Details of developed drive cycles

Category	Performance metric	Average speed (mph)	Duration (sec)	Drive Schedule ID
U_A_5	0.0276	7.32	147	605
U_A_10	0.0717	11.12	1945	610
U_A_15	0.0687	16.59	2184	615
U_A_20	0.0667	21.49	984	620
U_A_25	0.0888	23.67	430	625
U_A_30	0.0923	31.33	1054	630
U_A_40	0.1224	36.72	1327	640
U_A_50	0.1017	48.69	725	650
U_A_60	0.0305	57.91	174	660
U_F_0	0.041856	2.18	958	700
U_F_10	0.197489	14.86	1001	710
U_F_20	0.101263	23.20	1601	720
U_F_30	0.112362	25.32	1011	730
U_F_40	0.091954	43.38	1389	740
U_F_50	0.07532	47.59	2574	750
U_F_60	0.046149	63.62	1212	760
U_F_70	0.020934	76.81	540	770

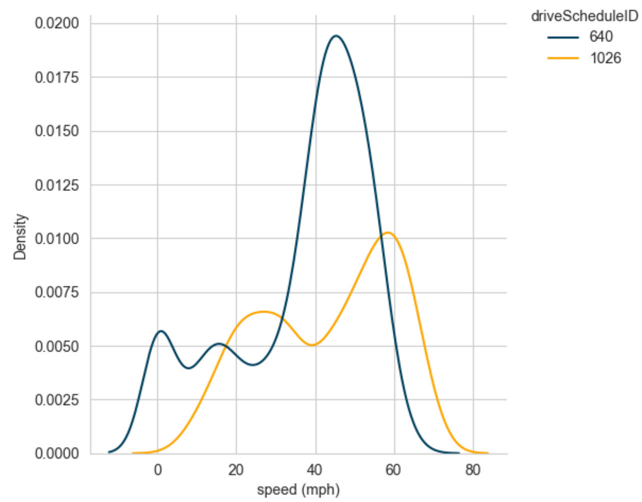
3.2 COMPARISON OF MOVES DEFAULT AND TEXAS-SPECIFIC DRIVE CYCLES

This section compares the MOVES default drive cycle and the Texas-specific drive cycle with the help of an example. For all the developed drive cycles, the reader is referred to Appendix A. Drive cycle ID 640 is chosen, which corresponds to the U_A_40 category. A drive cycle 1026 from MOVES defaults is selected, closest to the drive cycle 640 based on average speed and area type. Figure 5 (a) shows the speed profiles. The duration of the Texas-specific drive cycle is larger, with the average speed being 36.72 mph and 43.26 mph respectively for drive cycles 640 (MOVES default) and 1026 (Texas-specific). As plotted in Figure 5 (b), drive cycle 1026 has a higher density for larger speeds. Figure 5 (c) and (d) shows the operating mode distribution for the representative trip for category U_A_40 and for all the trips. Based on the comparison between Figure 5 (c) and (d), the research team concluded that the representative trip is close to the average operating mode distribution. On the other hand, Figure 5 (e) shows the operating mode distribution of the MOVES default drive cycle, which is considerably different.

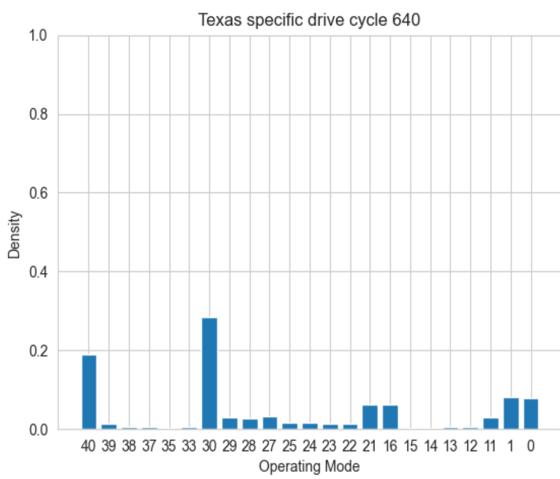
All the developed drive cycles are shown in Appendix A.



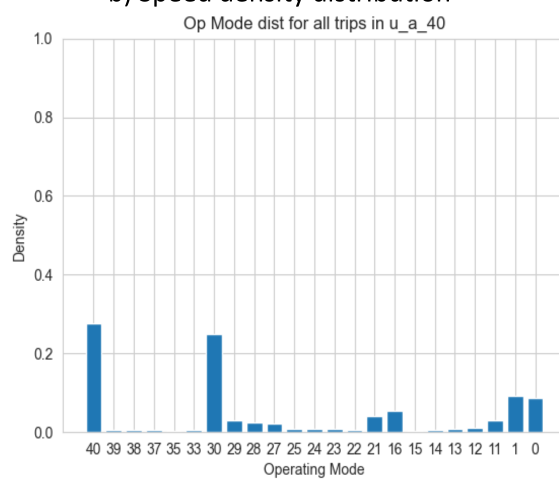
a) Speed profiles



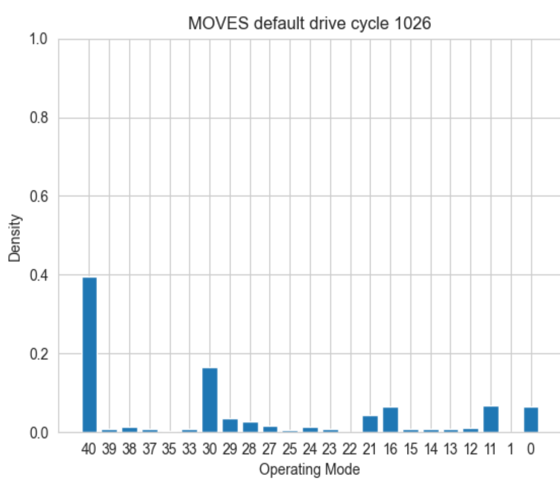
b) Speed density distribution



c) Operating mode distribution: 640



d) Operating mode distribution: all trips



e) Operating mode distribution: 1026

Figure 7: Comparison of MOVES default and Texas Specific trip

4 EMISSIONS SIMULATION

To assess the effect of drive cycles on emissions, both Texas-specific drive cycles and MOVES default drive cycles were examined in MOVES simulation. The drive cycles were only used for light-duty vehicles and unban road types. The details of the MOVES simulation are as follows:

- MOVES Version: MOVES4.0.1
- Calculation type: Emission Inventory Mode
- Domain/Scale: County scale run for Dallas County (County ID: 48113)
- Year: 2023
- Month: July
- Day: Weekdays and Weekends
- Pollutant of Interest: NOx, CO_2-eq, PM_{10}, $PM_{2.5}$, CO, VOC

Dallas County was chosen for simulations because it is an urban county and the Wejo data consists majority of urban trips. Two simulations were carried out, one with MOVES default drive cycles (default) and one with the Texas-specific drive cycles (specific). All the other MOVES input tables in the simulations were identical except the three tables related to drive cycles. The next section compares the emissions of selected pollutants in the above two simulations.

4.1 COMPARISON OF EMISSIONS

The output from MOVES simulations was post-processed to get the desired emission quantities. Figure 8 shows the monthly emissions on urban arterials and urban freeways for light-duty vehicles (passenger cars, passenger trucks, and light commercial trucks). The emissions on rural road types and other vehicle types are not shown because they were identical. A general trend can be seen in all the pollutants. The emissions using Texas-specific drive cycles were higher for arterials but lower for freeways. Overall, CO showed the largest increase in emissions from Light duty vehicles, with a 5.62% rise. The difference in NOx, VOC and CO2 equivalent was less than 1%.

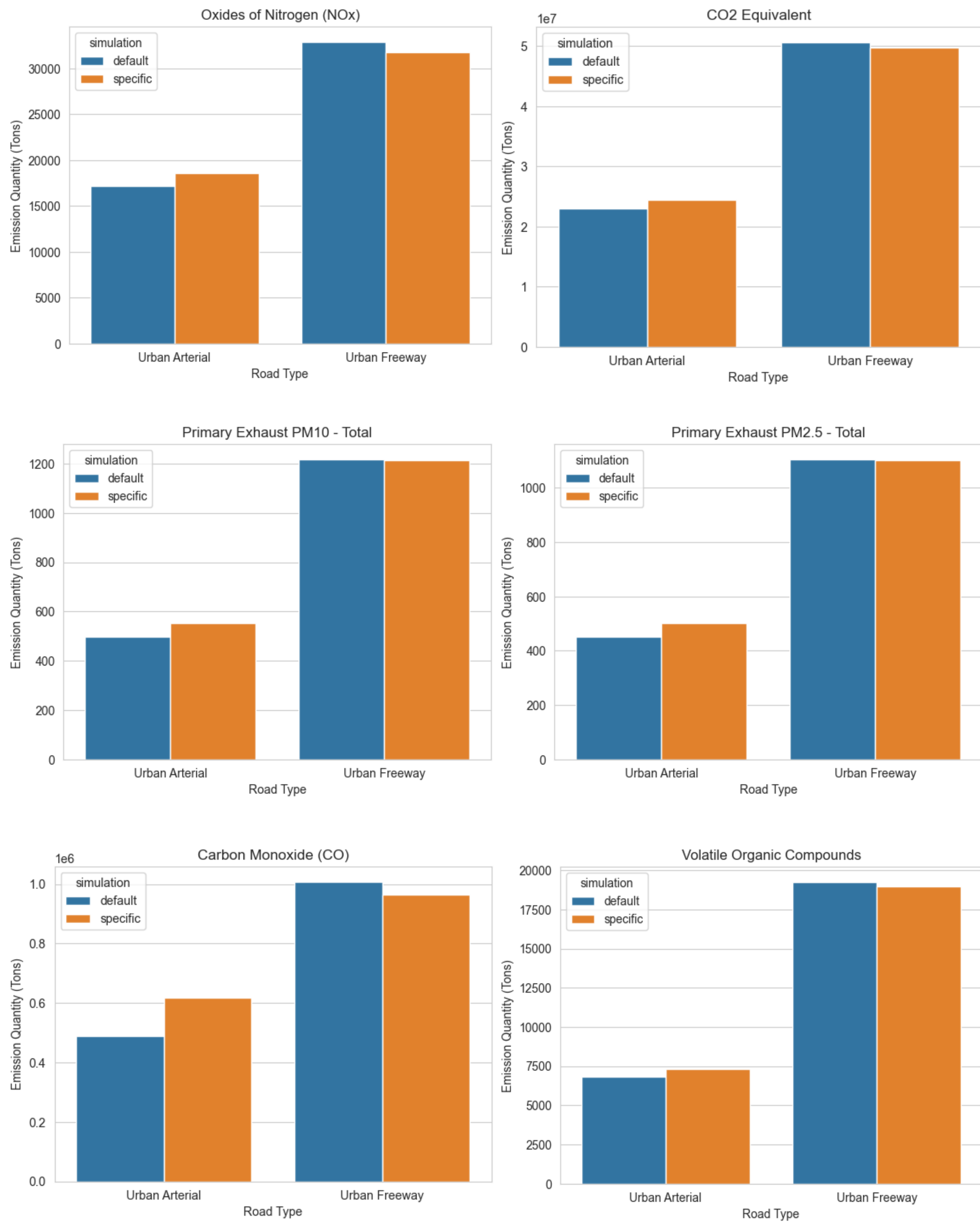


Figure 8 Monthly emissions estimated using MOVES default and Texas-specific drive cycles for Dallas-Fort Wort area.

In the case of $PM_{2.5}$ and PM_{10}, the difference in the emissions for urban freeways was small, however, the difference in the urban arterial was notable. Overall, the emissions of $PM_{2.5}$ and PM_{10} increased by 2.90% and 2.97%, respectively.

When the emissions from arterials and freeways are analyzed separately, for both $PM_{2.5}$ and PM_{10}, there is an 11% increase in arterial emissions and a 0.4% decrease in freeway emissions by using Texas-specific drive cycles. For NOx, there is an 8.36% increase in arterial emissions and a 3.61% decrease in freeway emissions. In the case of VOCs, there is a 7.17% increase in arterial emissions and a 1.43% decrease in freeway emissions.

Figure 9 shows the breakdown of PM emissions according to the source types. This was done to understand the contribution of considered source types in emissions and the differences caused. More than 70% of the PM emissions arising from LDVs come from passenger trucks. The higher emissions for urban arterials using Texas-specific drive cycles are evident in all the source types.

The increase in emissions on urban arterials and the decrease on urban freeways might be related to speed differences between MOVES default and Texas-specific drive cycles. As shown in Figure 10, once a vehicle starts moving, the emission rate decreases quickly, reaching its lowest values around 20-30 mph, depending on the pollutant. After passing a certain speed threshold, emission rates tend to increase. It is important to note that speed-emission rate curves can vary based on factors such as road types, time of day, season, and weather conditions. For example, although Figure 10 shows the highest emission rates at low speeds, other studies have found NOx emissions peak at higher speeds (22).

This variability highlights the need for localized data to accurately model emissions and develop effective mitigation strategies, especially in non-attainment areas. Incorporating Texas-specific drive cycles into MOVES allows us to enhance the precision of emissions estimates and better address regional air quality challenges. This approach emphasizes the importance of continuous data collection and analysis to adapt models to consider the local traffic patterns and environmental conditions.

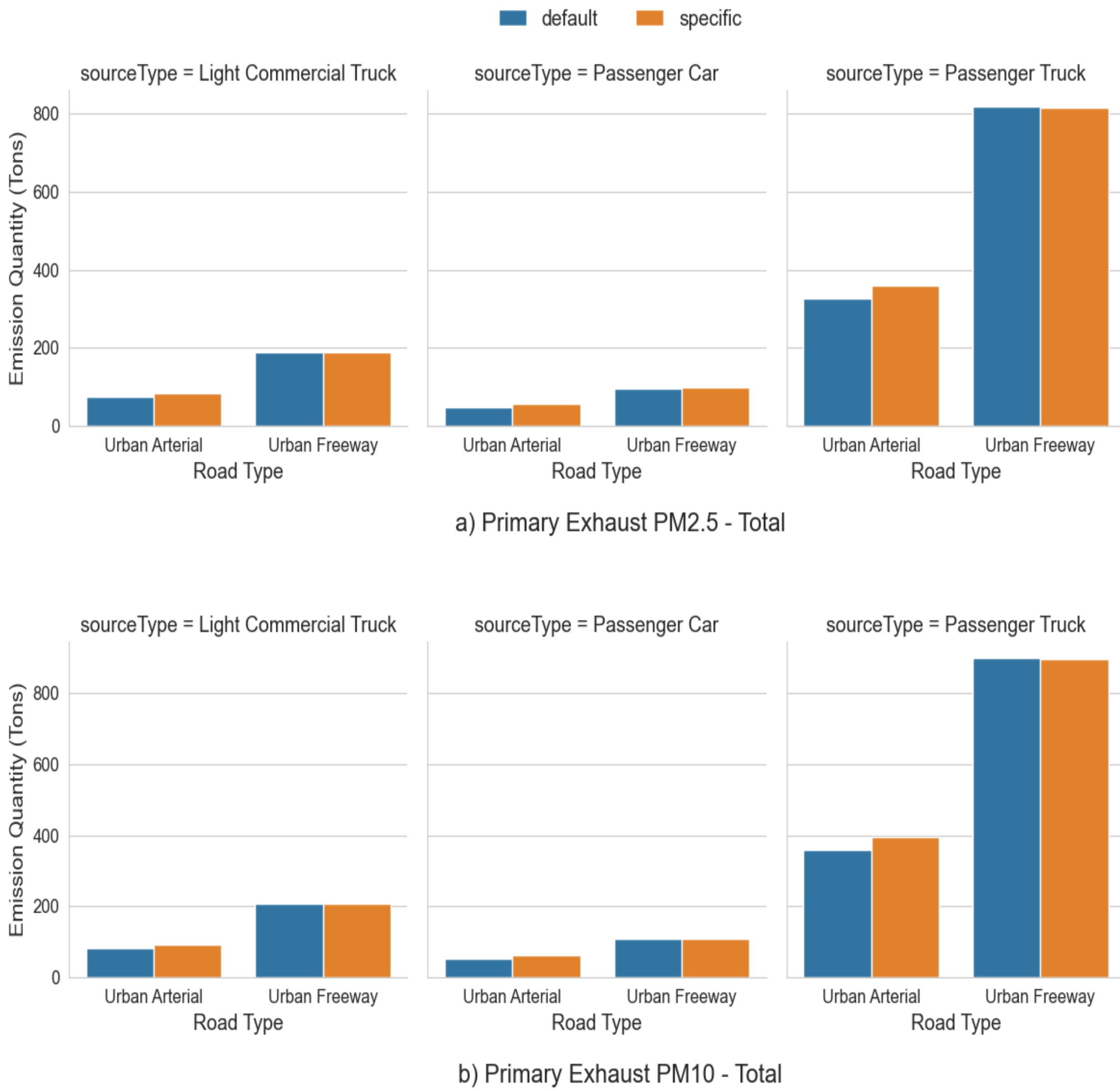


Figure 9 PM emissions for source types estimated using MOVES default and Texas-specific drive cycles for Dallas-Fort Wort area.

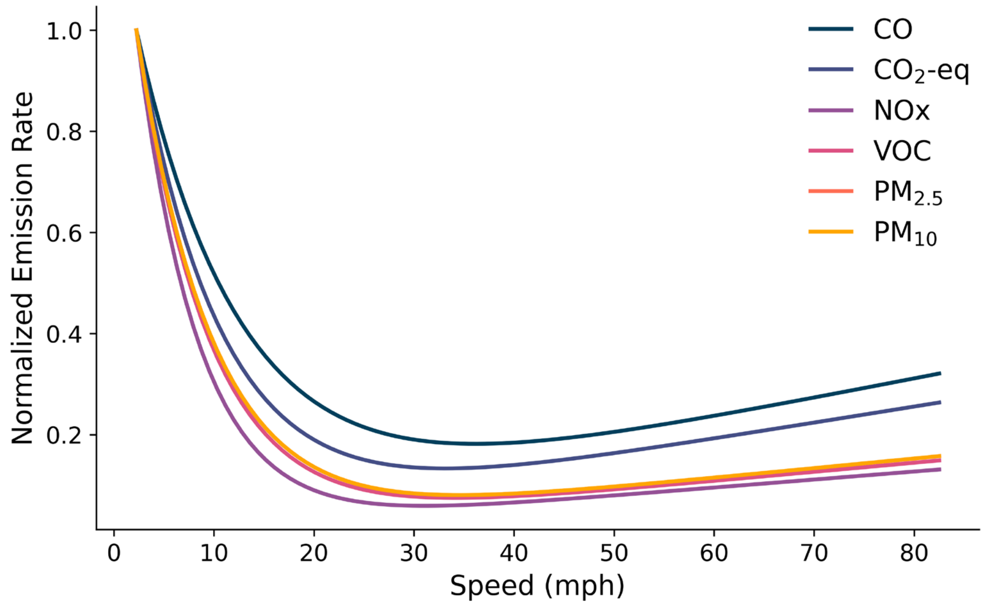


Figure 10. Correlation between normalized emission rate and speed in urban arterial roads.

5 CONCLUSIONS

To assess the emission estimation accuracy using MOVES default drive cycles, the main objective of this work was to develop drive cycles that best represent the driving conditions in Texas using the Wejo data. The developed drive cycles were further integrated with MOVES simulation for light-duty vehicles and urban road types. Emissions were compared by using Texas-specific drive cycles and MOVES default drive cycles. In general, the emissions using Texas-specific drive cycles were higher than MOVES default drive cycles for urban arterials and lesser for urban freeways. The total emissions were higher by using Texas-specific drive cycles for all the considered pollutants. CO showed the highest increase of 5.62% in overall emissions by using Texas-specific drive cycles. In the case of NOx and VOCs, the overall difference in emissions was less than 1%. However, for $PM_{2.5}$ and PM_{10}, the emissions were 2.90% and 2.97% higher with Texas-specific drive cycles, respectively. These differences could be important, considering the non-attainment of the considered area.

The developed drive cycles were based on operating mode distributions of thousands of trips and capture local driving conditions. The report demonstrates that the Wejo data can be used for drive cycle development. Furthermore, this work can be extended in several directions. One extension is to develop drive cycles for rural areas, as well as heavy-duty and medium-duty vehicles. Drive cycles can be developed for different categories. For example, one trip with uniform speed and another trip with some variance in speed can have the same average speeds, but their emissions can be different. Speed variance can be considered as another factor in drive cycle development and different drive cycles can be developed for the same average speed but different speed variances. Lastly, trips can be more selectively considered. The trips with extremely high or extremely low durations can be dropped, and drive cycle durations can be determined from average trip durations.

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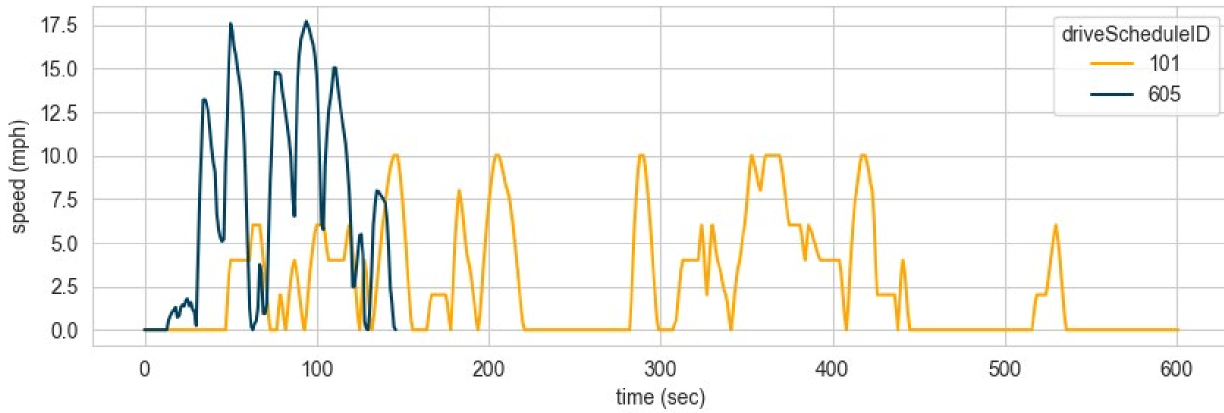
APPENDIX A. TEXAS-SPECIFIC DRIVE CYCLES

In this appendix, the developed drive cycles are plotted with the closest MOVES default drive cycles based on average speed. For some drives cycles, the closest MOVES default drive cycle could not be found. They are plotted alone.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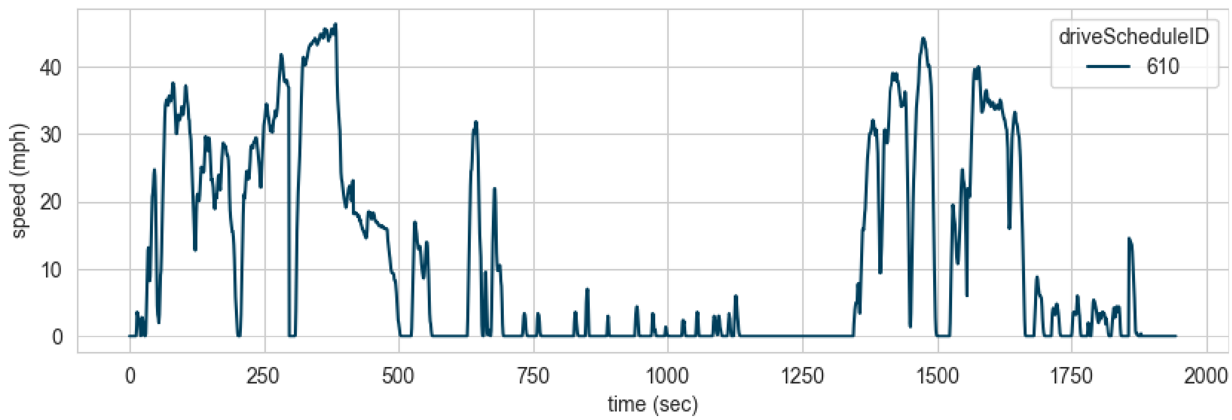
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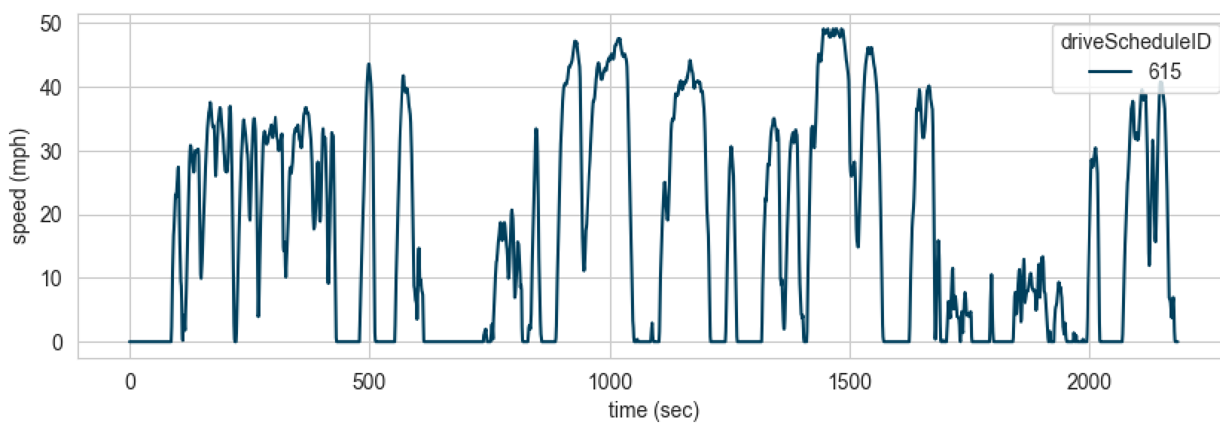
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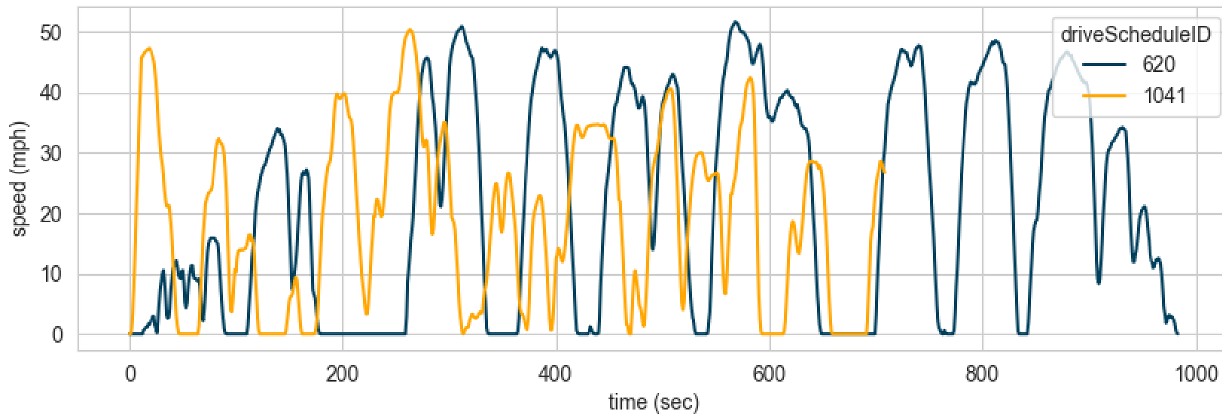

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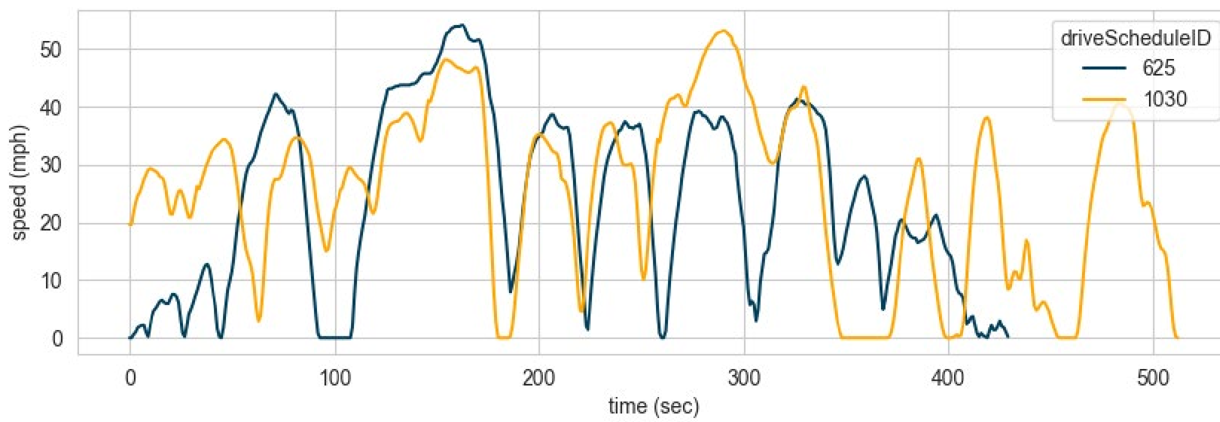

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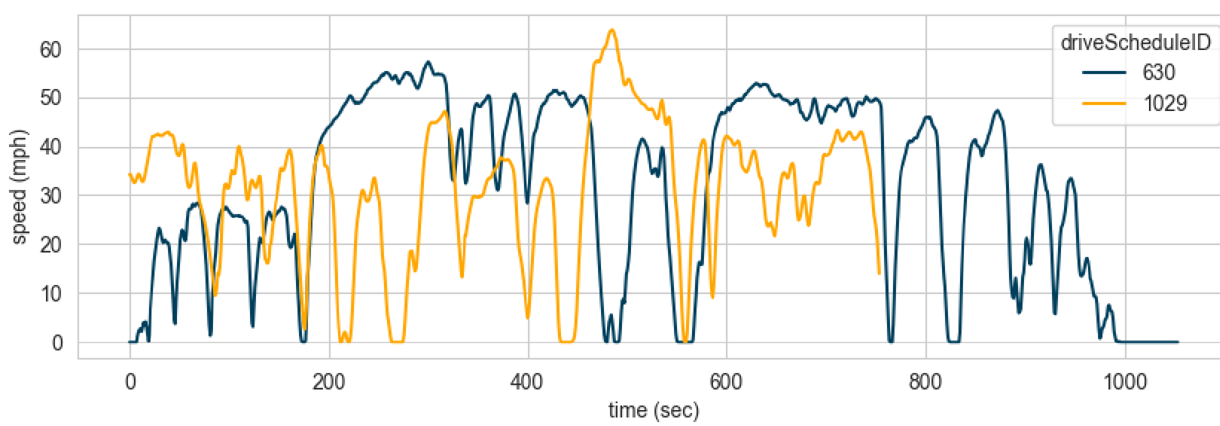

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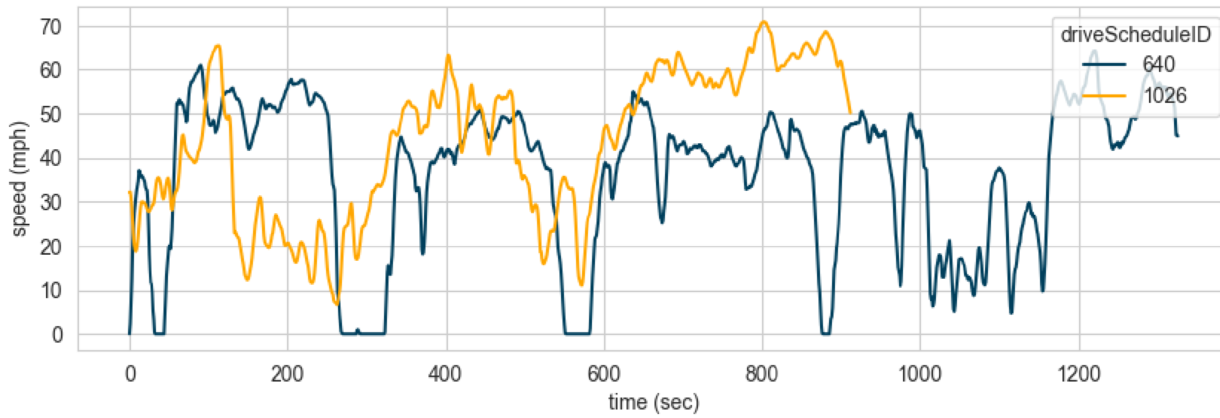
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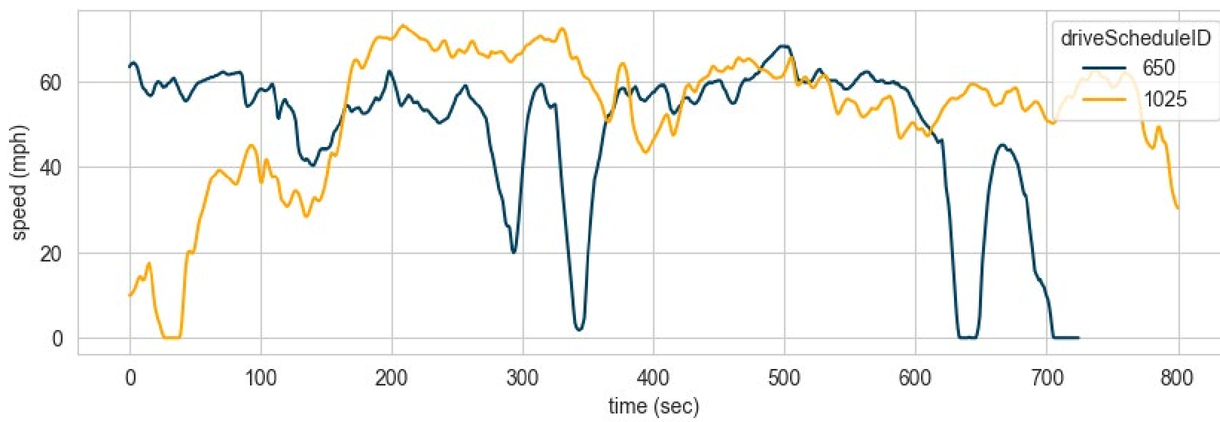
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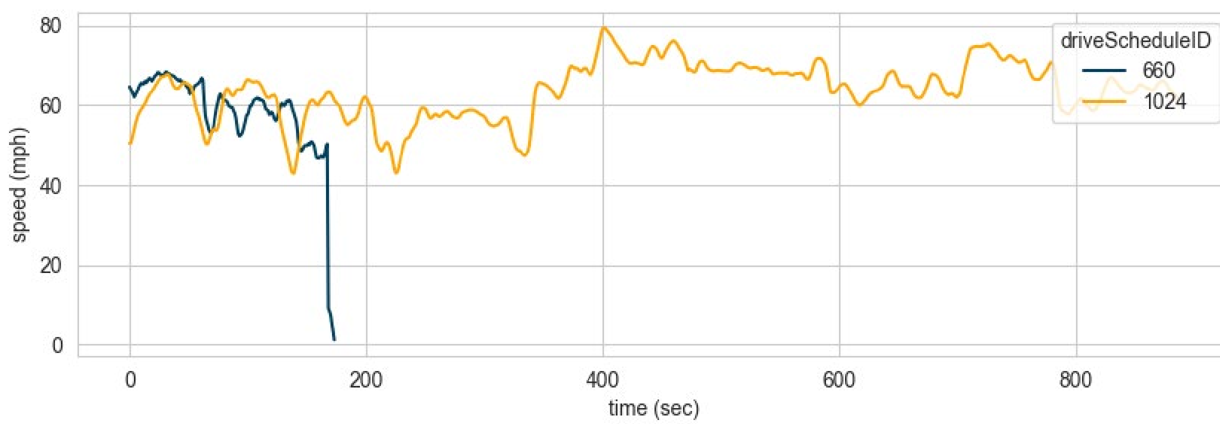
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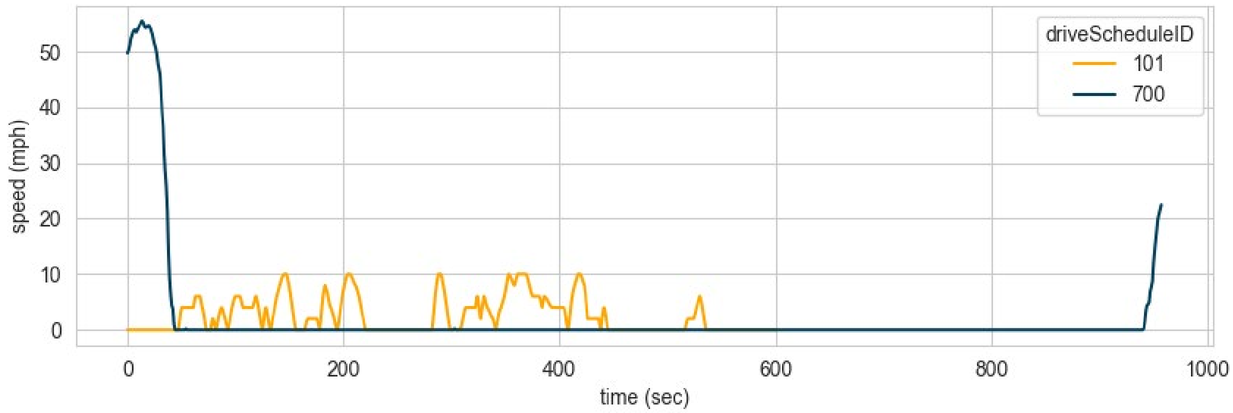
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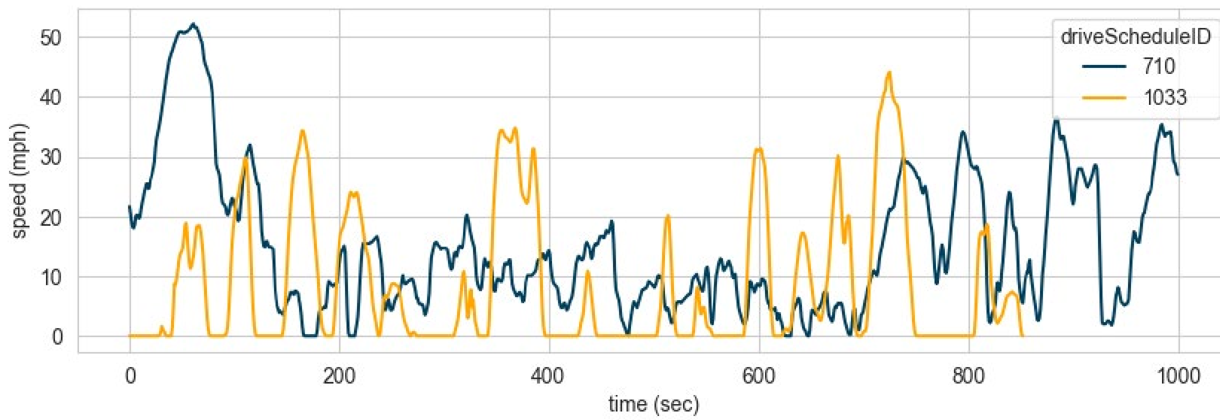
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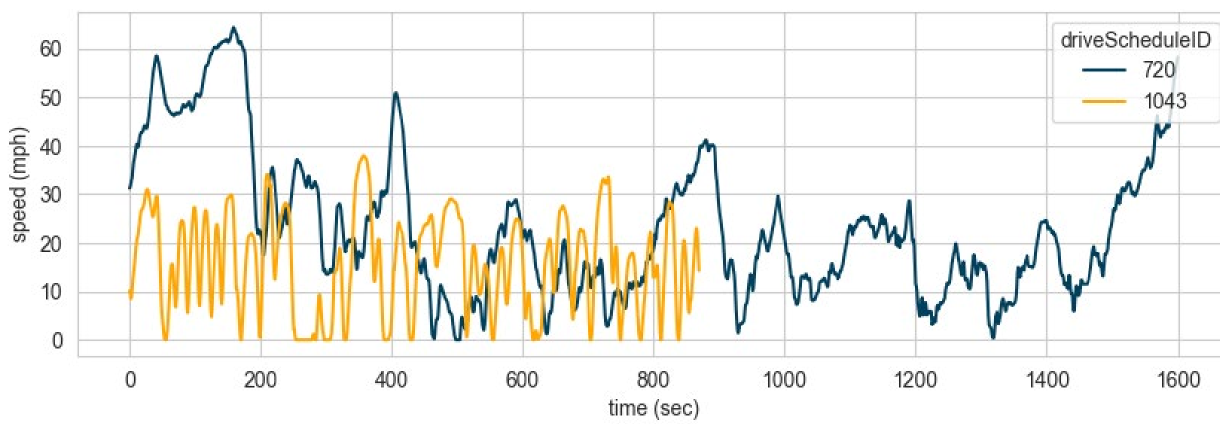
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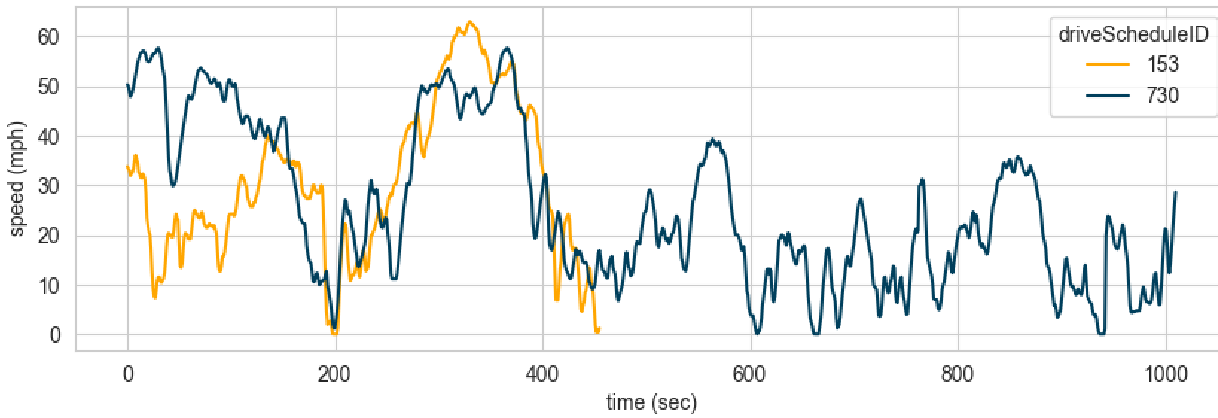
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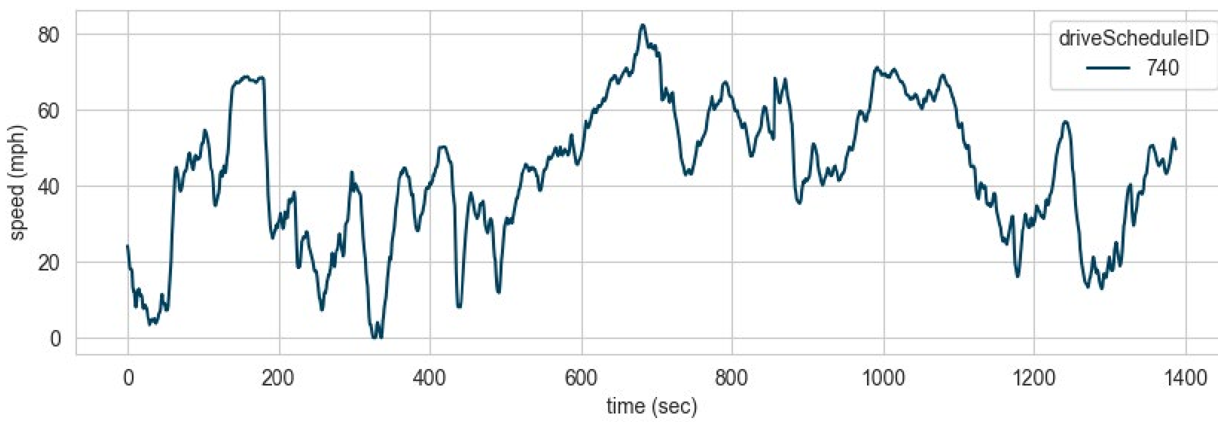
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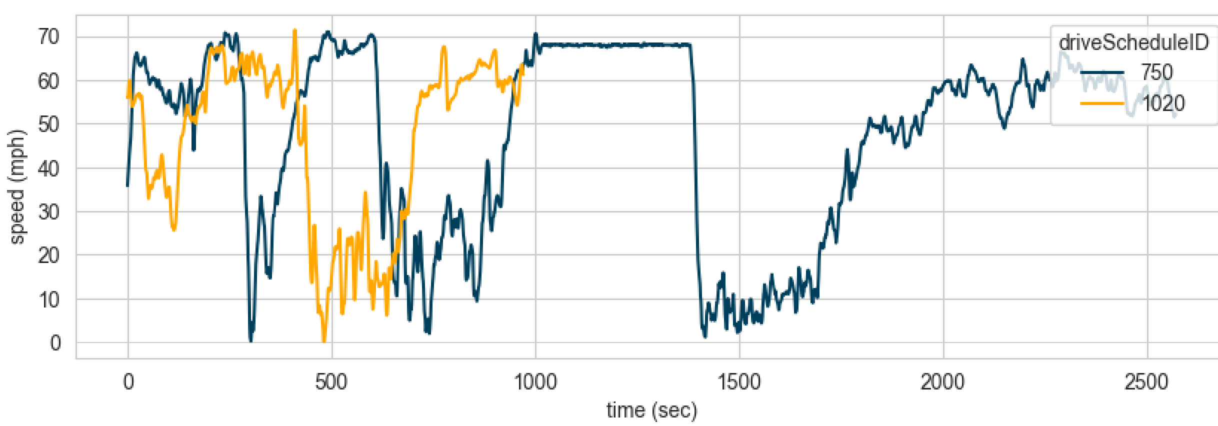
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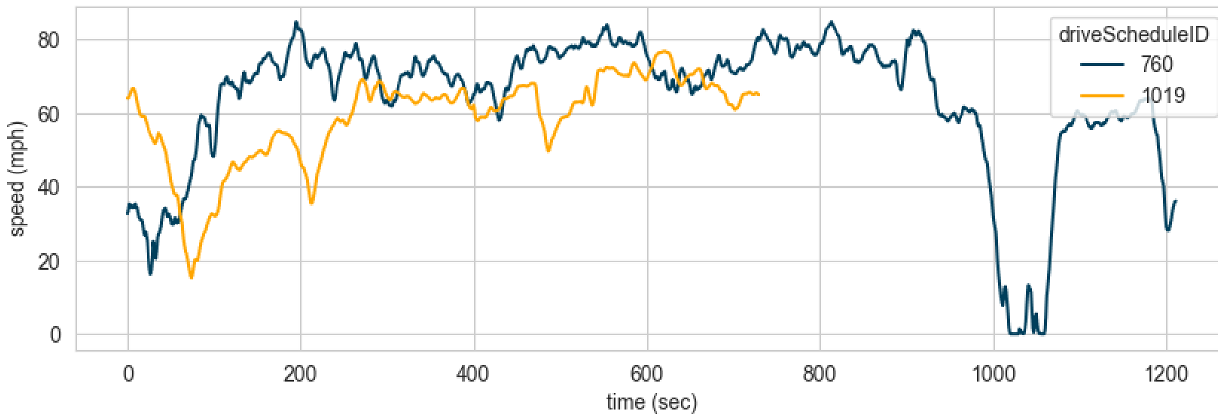
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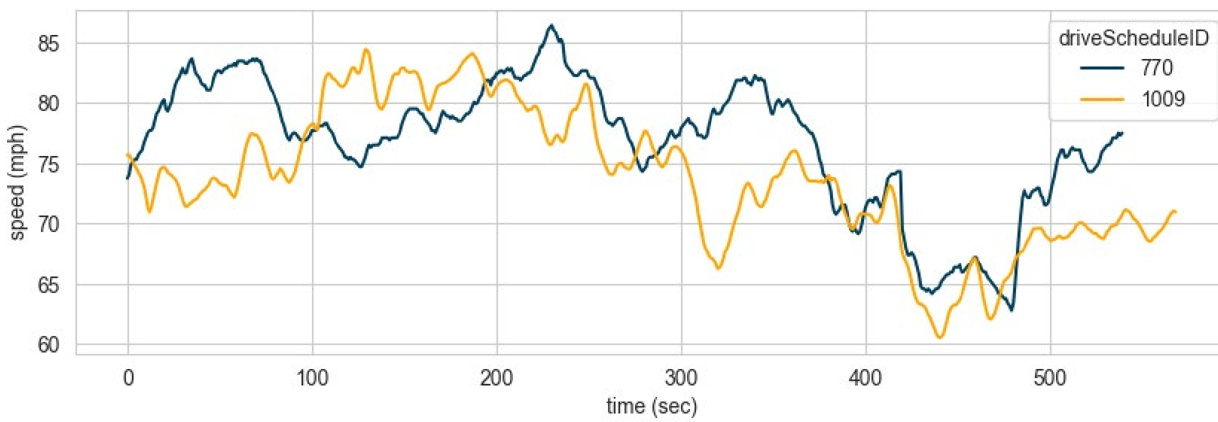
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