# DEVELOPMENT OF A DUTY CYCLE FOR THE DESIGN AND OPTIMIZATION OF ADVANCED HEAVY-DUTY PORT DRAYAGE TRUCKS

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## ABSTRACT

Hybrid-electric and electric trucks are potential technology solutions to reducing emissions at the ports. However, developing an advanced low emissions technology driveline entails thoroughly understanding typical truck operations in the real-world environment. This paper presents the work performed to develop a novel, more representative drayage duty cycle that characterizes drayage truck operations in the Ports of San Pedro bay. Unlike a conventional vehicle, an optimized hybrid driveline would require detailed understanding of not only torque requirements and vehicle speeds but also the potential recovery of dynamic brake energy, charging opportunities, stopping and idling times, and many other operational requirements. Keeping this in mind, our duty cycle incorporated real-world, near-dock activities of Class 8 drayage trucks such as daily hours of operation, mileage, altitude profiles of routes, and idling and key OFF patterns. The empirical duty cycle model was subsequently integrated with a complete vehicle simulation to explore the best solutions to minimize energy consumption for drayage applications in and around the ports. Our analysis indicated that trucks spent most of the generated power in overcoming aerodynamic drag and rolling resistance of tires for a complete drayage shift, and that electrical auxiliary loads dominated for near-dock operations due to idling and low speed profiles. Hence, achieving zero emissions near-dock operations entail focus on auxiliary loads and rolling resistance. Using simulations it was estimated that a hybrid truck with electrical power limited to about 100kW has the potential to deliver greenhouse gas emission reduction of about 30%.

*Keywords*: Port Drayage Trucks, Duty Cycle, Near-Dock Operations, Port Operations, Plug-in Hybrid Powertrain, Heavy-Duty Trucks, Volvo Group, Mack Trucks.

## INTRODUCTION

The ports of Long Beach and Los Angeles handle a third of the container port traffic in the United States [1]. Over 11,000 drayage Class 8 truck tractors move containerized goods between the two ports and a variety of businesses, terminals, warehouses, trans-loading facilities and container yards [1, 2]. In areas affected by air pollution, transportation using advanced technology and alternative fuels in port drayage trucks can be a step toward meeting the National Ambient Air Quality Standards for Ozone [3]. Drayage truck routes are characterized by small average distances, frequent stops, and prolonged idling, thereby making them good candidates for deploying plug-in hybrid technologies. In a technology research project funded by the South Coast Air Quality Management District (SCAQMD) [4] and the California Energy Commission (CEC) [5], the Volvo Group (herewith referred to as Volvo) adapted a plug-in hybrid driveline, successfully commercialized in the European transit bus market, to a North American heavy-duty truck platform for demonstration in port drayage applications. The vehicle was shown to operate in a zero-emission electric mode for limited distances at low speeds to circumvent the inefficiencies of the internal combustion engine. Using a hybrid electric powertrain for port drayage operations (and other local and regional haul routes) also has the benefits of reducing criteria pollutant emissions and lower fuel consumption. With the option to “plug-in” to the electric grid, the wheel-to-wheel emissions of the vehicle can be reduced even further. This paper presents the preliminary work done to better understand port drayage truck operations in the Ports of Los Angeles and Long Beach region, and to develop an empirical duty cycle to help the design and optimization of advanced heavy-duty port drayage trucks of the future.

## INITIAL MODEL FOR NEAR-DOCK DRAYAGE OPERATIONS

The initial duty cycle model was based on the drayage duty cycle statistics generated by TIAX [1]. TIAX collected over 1,000 truck trips during a four-week period and identified five distinct modes of operation based on vehicle speed - Creep, Low Speed Transient, Short High Speed Transient, Long High Speed Transient, and High Speed Cruise. Combinations of these operational modes were used to develop duty cycles that characterized three regions of operation -

- Near-dock (less than 6 miles from the port terminals),
- Local (between 6 and 20 miles from the port terminals),
- Regional (between 20 and 120 miles from the port terminals).

Making operation near the port zero emissions will reduce health risks and cut air pollution produced for a global seaport complex. The greatest benefits of the plug-in hybrid driveline are expected in the region of operation defined by TIAX as near dock, which motivates the focus of this project.

Most of the port terminals are located on or near the Terminal Island which is a largely artificial island located in Los Angeles County, California, between the neighborhood of San Pedro in the city of Los Angeles, and the city of Long Beach [6]. Terminal Island is roughly split between the Port of Los Angeles and Port of Long Beach (Figure 1). Land use on the island is entirely industrial and port-related, and is a part of most drayage routes. Terminal Island is connected to the mainland via three road bridges. To the west, the distinctive green Vincent Thomas Bridge, the fourth-longest suspension bridge in California, connects it with the Los Angeles neighborhood of San Pedro. The Gerald Desmond Bridge connects the island with downtown Long Beach to the east. The Commodore Schuyler F. Heim Bridge joins Terminal Island with the Los Angeles neighborhood of Wilmington to the north.

**FIGURE 1 Map of the ports of Long Beach and Los Angeles. The Ports region is within the blue colored polygon. Terminal Island, where a majority of terminal containers are located is within the green colored polygon. The three bridges that connect Terminal Island with the mainland are marked by magenta rectangles.**

Duty cycle models for near-dock and local operation were created based on the information provided in the TIAX report. The purpose of these duty cycles was to perform basic energy consumption analysis and size the electrical and hybrid components on the truck. Since the Global Positioning System (GPS) locations were not provided in the TIAX report, map information was used to create arbitrary start and end points in the ports region. The initial model was based on the TIAX near-dock duty cycle for a route involving the Gerald Desmond Bridge (Figure 2). An arbitrary turn-by-turn route was designed to emulate a typical near-dock operation and estimate the amount of idling time.

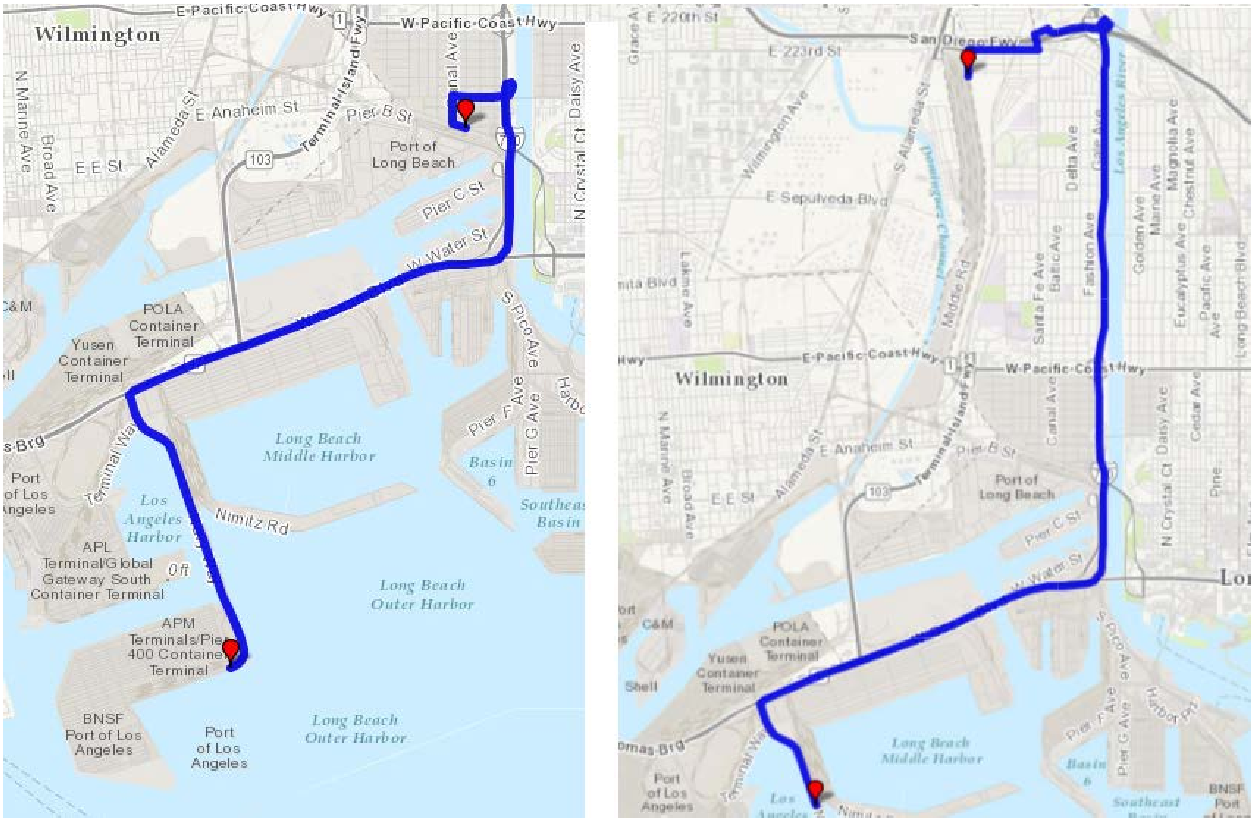


**FIGURE 2 Maps of near dock and local duty cycles created based on TIAX report. The map is only for location information. The speed profiles were taken from the TIAX report.**

The speed profiles for these duty cycles was created using the TIAX operating modes like Creep, Low Speed Transient, Short High Speed Transient, Long High Speed Transient, and High Speed Cruise, and compared with our simulated model (Table 1). It was observed that the speeds computed using our model matched those obtained from the TIAX report with the exception of two operational modes. This was because while the actual speed of the truck was recorded in the TIAX report, the target speed was used as input to the simulation model.

| | | Creep | | Low Speed Transient | | Short High Speed Transient | | Long High Speed Transient | | High Speed Cruise | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TIAX | Simulation | TIAX | Simulation | TIAX | Simulation | TIAX | Simulation | TIAX | Simulation |
| Average Vehicle Speed | m/s | 0.36 | 0.13 | 1.92 | 1.67 | 5.41 | 5.42 | 6.12 | 6.83 | 14.71 | 14.41 |
| Average Moving Speed | m/s | 1.21 | 1.15 | 3.4 | 3.15 | 7.64 | 7.38 | 8.36 | 9.36 | 16.94 | 16.89 |
| Maximum Speed | m/s | 2.15 | 2.19 | 7.38 | 7.6 | 18.46 | 18.15 | 21.32 | 20.79 | 26.2 | 26.15 |
| Total Time | s | 363 | 334 | 592 | 550 | 1385 | 1420 | 2956 | 2605 | 5577 | 5544 |
| Stops | | 3.3 | 3 | 8.5 | 9 | 16.2 | 15 | 29 | 29 | 22.7 | 24 |
| Trip Length | m | 48 | 44 | 933 | 921 | 6727 | 7690 | 18169 | 17792 | 81416 | 79882 |

**TABLE 1 Comparison of observed (from the TIAX report) and simulated speed profiles for different modes of operation.**

## SHORTCOMINGS OF DUTY CYCLE FROM THE TIAX REPORT

Firstly, it was obseved that speed and altitude profiles of the roads tremendously influenced the true power requirements and potential kinetic energy recovery that can be expected, thereby affecting the performance of the hybrid electric vehicle. For example the three bridges from which the trucks enter and exit the terminal island have significant altitude changes. Of the three bridges, the Gerald Desmond Bridge is considered most challenging (in terms of energy consumption consideration) with 5.5 to 6% maximum grades requiring heavy-duty trucks to slow down and use engine power above 350 hp approximately 50% of the time it takes to cross the bridge [1]. It is hence important to find out exactly how the trucks are using these bridges in their daily operations.

Secondly, the TIAX report did not include data about the number, location, and duration of stops. Furthermore, data indicating the time periods when the vehicle was stopped with the key in the OFF position was missing. This is a critical piece for the design of hybrid and completely electric vehicles because we do not expect the hybrid electric vehicle to be keyed OFF as often. While the conventional diesel truck may have almost zero energy consumption when the truck is stationary with the engine turned OFF, the hybrid electric may still have significant electric loads such as air conditioning, battery cooling, to name a couple.

Thirdly, understanding and incorporating operational constraints and parameters into the duty cycle is imperative to get the real picture with regards to energy consumption. For example, knowledge of the distance travelled by the truck between two charging opportunities will be an important consideration. This entails modeling complete operation cycles as time periods between two successive charging periods. The next charging opportunity will depend on the location of the charging infrastructure and the time required to charge back up to full capacity. So, recording and analyzing daily operation cycles, frequency of visiting a known parking location, travel times between the known parking location and the ports, etc., are needed to model the duty cycle accurately.

With this in mind, we decided to collect more information about drayage truck operations in the ports of San Pedro bay.

## DATA COLLECTION

Discussions with a major local fleet owner/operator helped gain a deeper understanding of drayage duty cycle characteristics not captured by the initial model. This activity motivated data logging on commercially operated drayage trucks to generate a more accurate representative duty cycle of drayage operation near the ports.

Specifically, it was learned that

- A single shift typically ran for about eight to nine hours, and involved an average of three trips to the ports region.
- Grid charging using current infrastructure can only be done when the shift is over when the vehicle returns to base.
- The Gerald Desmond Bridge is the most challenging bridge when it comes to entering Terminal Island, an area of intense activity for the ports of Long Beach and Los Angeles.

- Drivers may not be using the Gerald Desmond Bridge as often as assumed in the initial model.
- The exact usage distribution between the different bridges is not well known.
- The amount of time the vehicles are stationary (defined as engine idling or with key OFF) is much larger than what was computed using TIAX data.

Three Mack trucks (Model Year / Model: 2013 / CXU613 [7]) were instrumented for the purpose of logging data. Data was logged using DataWorks data recorders connected directly to the J1939 controller area network (CAN) [8]. Data logging was continuous at a frequency of 1 Hz even when the vehicle was stopped and the engine was turned off. This was done using a small 12V battery that could keep the data acquisition system running when the trucks were powered OFF. The battery charged itself from the truck when the engine was ON. A total of 198 hours and 1,951 miles of port drayage operation were logged over 24 days.

Data collection was aimed at understanding the overall energy demands and operational requirement of a vehicle as well as the impact of the operation terrain. Keeping this in mind, the following parameters were logged - time and date, vehicle location (in terms of GPS coordinates), speed (mph), distance traversed (mi), engine parameters (torque demand, fuel rate, and speed), brake usage (pedal and ON/OFF positions), accelerator pedal position, cooling fan status, barometric pressure, and ambient temperature.

Another novel component was the altitude data collection. Using GPS coordinates and barometric pressure measurements [9], complete altitude profiles of the major access routes to and from the ports of Long Beach and Los Angeles were created. GPS and pressure data was collected using an ISAAC Instruments data recorder [10] mounted on a passenger car. The data recorder was equipped with a GPS receiver and an Omega pressure transducer [11] and data was collected at a sampling frequency of 1 Hz.

To enhance the quality of data collected, the pressure transducer was placed inside the vehicle on the rear seat of the car and kept away from the Heating, Ventilating, and Air Conditioning (HVAC) vents. The windows were rolled up and the HVAC system was set to 70ºF and put on recirculation mode. The fan speed was set at constant low speed with the automatic fan speed feature disabled. To avoid undesirable pressure changes, care was taken to ensure that the vehicle did not accelerate nor decelerate too quickly. Lastly, the GPS sensor was placed such that it had ample view of the sky and the number of satellites in view of the GPS receiver was recorded to check for accuracy. Changes in the atmospheric pressure are correlated to changes in the altitude. The barometric pressure, $P_{sta}$ (in mbar) was converted into altitude, $h_{alt}$ (in feet) using the equation from [3]:

$$h_{alt} = \left(1 - \left(\frac{P_{sta}}{1013.25}\right)^{0.190284}\right) \times 145366.45 \quad (1)$$

By matching GPS coordinates, almost all data points were assigned an altitude. Where the altitude data was not collected, for instance, inside container terminals and truck yards, the altitude was extrapolated linearly from the last and next point where altitude data was available.

## MODELING REPRESENTATIVE DUTY CYCLES

This section presents the development of representative duty cycles for drayage operations, one of the key contributions of the paper.

A “drayage shift” is defined as the period from when the driver leaves the base for the first time and returns back after the last run. A total of 24 port drayage shifts were analyzed both quantitatively and qualitatively. The analysis of the logged data helped better understand the opportunities and challenges for truck performance that need to be considered when designing a hybrid vehicle for port drayage operations. For example, to quantify the duration of operation in an “electric” mode relative to the hybrid mode, it is important to characterize the different operations during a typical drayage shift, its route, speed profiles, and powertrain. The physical dimensions of the battery are correlated to the duration of the shift, the potential for brake energy recovery, and the electric motive power requirements.

During an average drayage shift, a truck enters the ports region an average of 2.7 times and Terminal Island 2.5 times. This is consistent with the information obtained from the fleet operators that stated that the drivers are able to pick up about 3 containers per shift on average. A typical port drayage shift was 81.3 miles long. Of these 81.3 miles, 28.4 of them were in the Ports Region while 20.2 of these 28.4 miles were on Terminal Island. The average port drayage shift lasted a total of 495 minutes (8 hours 25 minutes). The shortest duration cycle, a day cycle lasted only 214 minutes (3 hours 34 minutes) while the longest duration cycle, a night cycle lasted a total of 637 minutes (10 hours 37 minutes). The summary parameters were averaged over all port drayage shifts (Table 2).

While an average port drayage truck drove only 35% of the miles in the ports region and 25% of the miles on Terminal Island, it spends 59% of the time in the ports region and 44% of the time on Terminal Island. On the average, each drayage truck spent 56% of the time idling (with the engine ON, not moving) or key OFF (with the engine OFF, not moving). At the ports region, 65% of the time is spent idling or key off while trucks are queuing to enter terminals or waiting to pick-up or drop off containers (Figure 3).

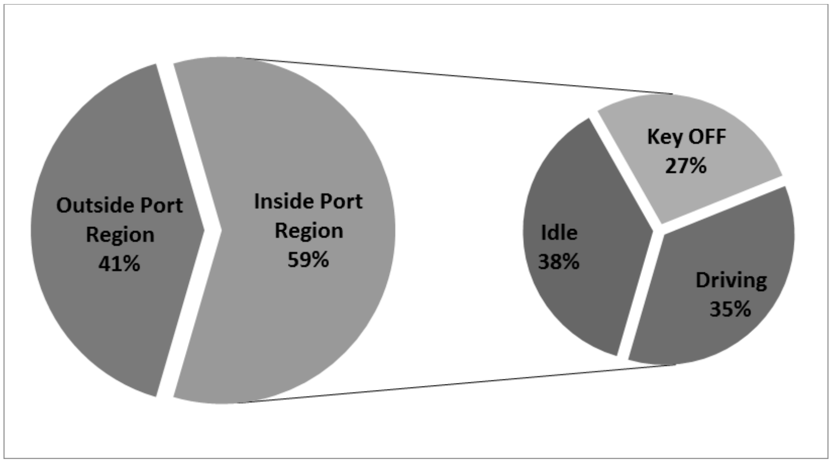


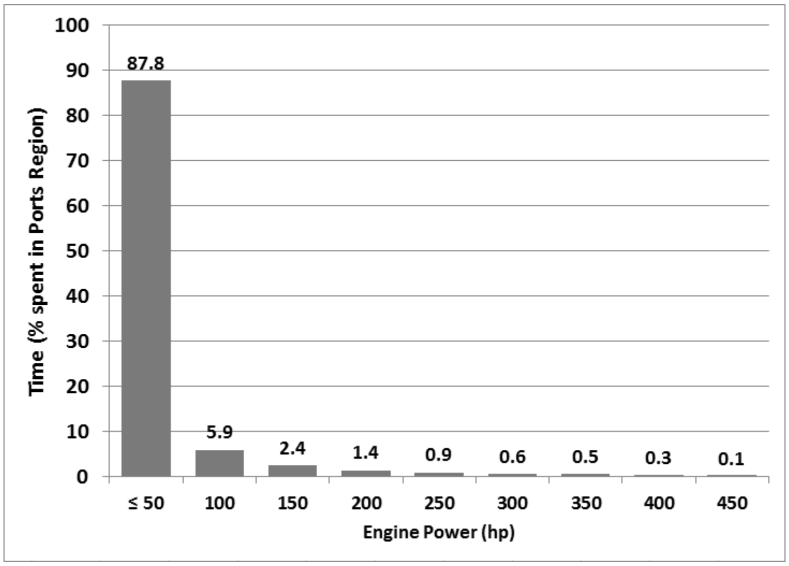
**FIGURE 3 Time breakdown of an average drayage shift and during near-dock operations.**

In order to access Terminal Island, one of three access bridges - the Vincent Thomas Bridge, Commodore Schuyler F. Heim Lift Bridge, or Gerald Desmond Bridge – must be crossed. It was found that the Commodore Schuyler F. Heim Lift Bridge was used 65% of the time, while the Vincent Thomas Bridge was used 24% of the time, and the Gerald Desmond Bridge was used only 11% of the time. The Commodore Schuyler F. Heim Lift Bridge was actually used in all but one duty cycle during this particular data collection period.

### Truck Speed and Engine Power Demands

The engine power demand observed on the test trucks when operating in the ports region was below 150 hp for an average of 96.1% of a drayage shift (Figure 4). Although there are numerous factors such as battery state of charge that impact the ability to operate in a completely electric mode, our observations indicate that a hybrid powertrain with a small electric motor (half of the reference diesel engine power rating) can provide a lot of opportunities for pure electric operation in the ports region.

Vehicle speed distribution is another important factor because the power usage is more at higher speeds. The test trucks spent an average of 93.1% of their operating time in the Ports Region at speeds below 30 mph (Figure 4). Upon further analysis, it was inferred that the Seaside Freeway, the major roadway running the length of Terminal Island and connecting the three bridges, is a high speed road with vehicles regularly traveling upwards of 50 mph. This section of road is the main reason for the high speed and power demand observed during operation in the ports region.



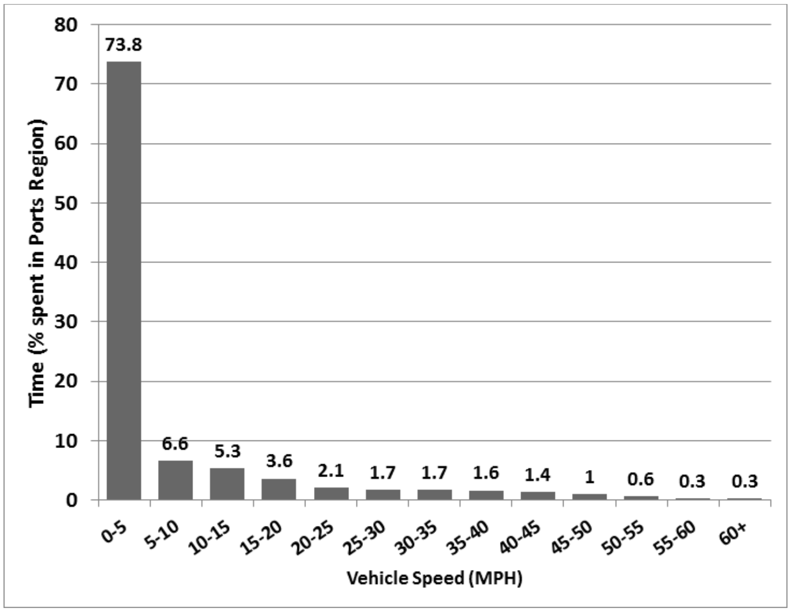


**FIGURE 4 Distribution of engine power demand and vehicle speed observed during operation in the ports region.**

## Selection of the Most Representative Duty Cycle

Operation close to the docks was the focus to select the most representative duty cycle. Specifically, it was decided to not include drayage shifts in which the truck travelled far from the Los Angeles region (Figure 5). This is because the electrical components of the truck would be used mostly near the dock. Farther from the dock region, the additional portions of the trip mainly included highway driving which would not have a major influence on the design and optimization of the electrical system on the truck. It was also decided to focus on shifts that used the Commodore Schuyler F. Helm Lift and Vincent Thomas Bridges because the Gerald Desmond Bridge appeared to be used most often when trucks travelled far from the Los Angeles region. Among the drayage shifts that fit these criteria, the most representative duty cycle was chosen to be the one where the summary parameters (i.e., distance travelled in the ports region, idle time, number of trips to the terminal, etc.) were closest to the average values (Table 2). Using the logged GPS coordinates, a travel route for each drayage shift was generated using the online GPS Visualizer tool [12]. GPS Visualizer generates a color-coded map using trip parameters such as speed, engine power, or altitude for the corresponding GPS coordinates. Visual inspection of these travel routes was also used to confirm the selection.

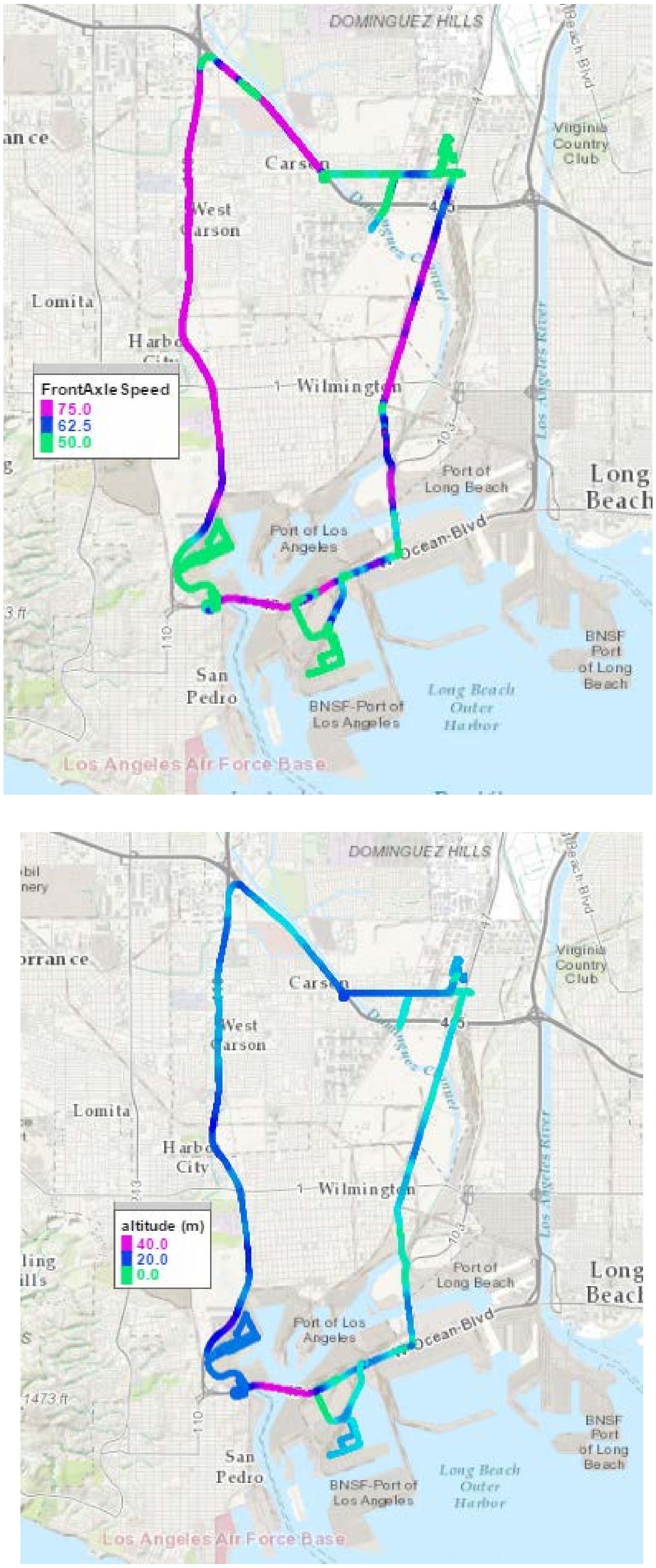


**FIGURE 5 Map of the most representative duty cycle. The first screenshot is colored according to the front axle speed of the truck in km/h. The trace on the second screenshot is colored according to the altitude of the road in metres. Please note that some portions of the shift have been removed.**

Compared to the averaged values, the most representative duty cycle selected covers fewer miles. Less time is spent on Terminal Island but more time is spent within the ports region. Specifically, the drayage shift selected to be the most representative duty cycle includes operations at the Port of Los Angeles terminals west of Terminal Island. The most representative duty cycle also includes two trips to the Ports Region and to Terminal Island and only used the V. Thomas and the C. Helm bridges.

Compared to the duty cycle model created using data from the TIAX report [2], our model is based on a longer distance traveled during a shift. Furthermore, our model includes key OFF operation that represents about 28% of the total drayage cycle duration, which is critical in designing components and control strategies for electrified vehicles. Adding a realistic altitude profile to the speed profile allows more precise analysis of potential brake energy recovery. It also provides a tool to verify the performance of various driveline concepts against the baseline vehicle e.g. gradability, acceleration from a stop on an uphill, trip time, which are all critical to the successful adoption of new technology in fleets.

| **Summary parameters** | **Average** | **Most Representative** |
|---|---|---|
| Total Duration | 495 min | 517 min |
| Time in ports region | 292 min | 356 min |
| Time on Terminal Island | 219 min | 91 min |
| Distance | 81.3 mi | 61.2 mi |
| Distance in ports region | 28.4 mi | 20.4 mi |
| Distance on Terminal Island | 20.2 mi | 8.9 mi |
| Total Idle Time | 172 min | 179 min |
| *Idle Time in ports region* | *110 min* | *127 min* |
| *Idle Time on Terminal Island* | *89 min* | *46 min* |
| Total Key OFF Time | 104 min | 146 min |
| *Key OFF Time in ports region* | *80 min* | *146 min* |
| *Key OFF Time on Terminal* | *53 min* | *16 min* |
| Times Entered Ports Region | 2.7 | 2.0 |
| Times Entered Terminal Island | 2.5 | 2.0 |
| Times used V. Thomas Bridge | 24% | 50% |
| Times used C. Helm Bridge | 65% | 50% |
| Times used G. Desmond Bridge | 11% | 0% |

**TABLE 2 Summary parameters over all port drayage shifts**

## EVALUATION OF THE REPRESENTATIVE DUTY CYCLE

A hybrid or completely electric drayage truck will need to have sufficient battery capacity to operate between charging opportunities. Given the current infrastructure constraints, the only feasible solution is to charge the batteries using the grid electricity when the vehicle is parked at the base location. For this reason considering the full shift approach and accounting for key OFF and idling is critical.

Based on the data collected it can be inferred that drayage trucks do not operate continually and there are rest periods of sufficient durations before they get on their routes. The data indicated that there was no more than one shift per 24 hours and that on average the trucks returned to the base within less than 9 hours. This observation implies that there is no obvious opportunity for fast charging in the current operational model. The exact routing and dispatch of the trucks is typically not determined far in advance. Moreover, the waiting time for picking up or dropping off containers at terminals is not predictable. Organizing data by shifts and embedding it into the duty cycle enabled a thorough performance analysis that was previously not possible in the TIAX study.

The data indicates that drayage trucks tend to idle or stop for extended periods of time near the entrance or exit of the terminals. While this could be a potential place for charging truck batteries, implementing such functionality would require considerable changes to the existing infrastructure and operation.

A fundamental design consideration for a hybrid driveline is the strategy to divide the motive power between the electric motor and the internal combustion (IC) engine. In general, it would be more efficient to use the IC engine during high speed operations and torque conditions. From the previous section we conclude that drayage trucks typically operate at low speeds and power near the terminals. For this reason, it is desirable to use the electric motor when operating near the terminals, while using the IC engine and brake regeneration to recharge the batteries when the truck is away from the terminals operating at higher power and speeds.

An important criterion that impacts the cost and performance of the hybrid truck is the size of the electrical components, particularly the battery. Because it is more efficient to use electric propulsion when the truck operates near the ports, it was decided to size the battery for maximum continuous electric propulsion. Subsequently, data analysis revealed that the battery has to be sized for at least two consecutive port visits that seemed to be a common occurence. Figure 6 shows the battery state of charge for one and two consecutive port visits using complete vehicle simulations. Such performance insights and analysis could not be performed using the TIAX data because it is broken down into segments where information about such operational requirements is not available.

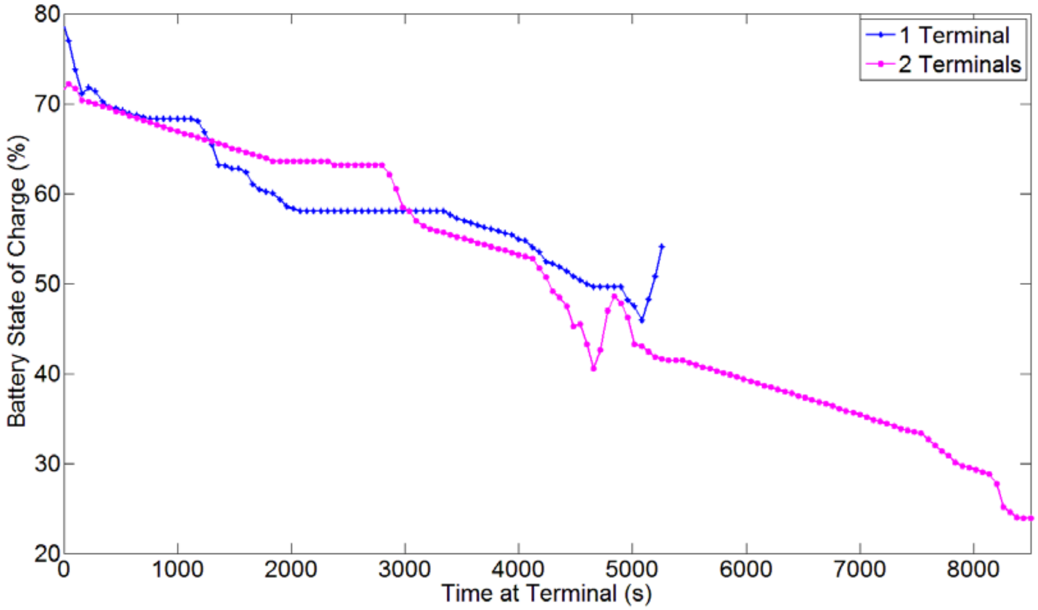
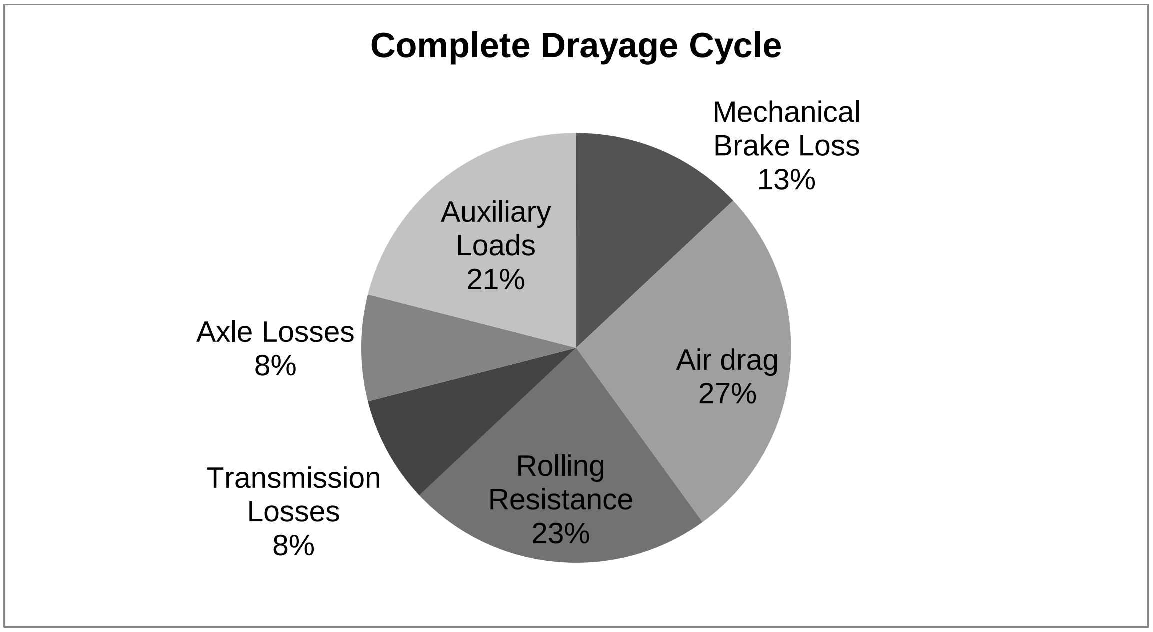


**FIGURE 6 Simulations of the battery depletion in the terminals using the most representative cycle. The simulation shows that the battery is large enough to last 2 trips to the terminal (magenta).**

Drayage routes include segments that have very different speed and torque profiles, thereby necessitating the hybrid vehicle controller to behave very differently at different locations. When the hybrid driveline is used in this manner, it is more beneficial to look at the total emission and reduction in the fuel consumption for the whole operation as the key performance indicators. Measuring fuel consumption and emissions for different segments may not tell the full story. For example, while operating in the port region where there are frequent stops, slow speeds and idling, the exhaust system may cool down leading to higher emissions when the truck enters a highway and the engine kicks in. Similarly, the engine torque may be used to charge the battery when the truck is driving on a highway so as to compensate for low speed operations in the port which tend to use more electric power. Measuring the performance of a plug-in hybrid truck using zero emission or pure electric range is therefore not necessarily indicative of the real impact potential of hybrid driveline on emissions and fuel consumption. Therefore, one should optimize the charge balance strategy based on the overall duty cycle. This can only be performed if we have a complete duty cycle as presented in this paper. Because information can be lost during the transition and the ordering of the various  segments, data analaysis based on completed duty cycle is recommended.

Our analysis indicated that heavy duty trucks spend most of the power generated by the driveline to overcome aerodynamic drag and rolling resistance of tires over the complete drayage cycle (Figure 7). During operation near the docks power consumed by electrical auxiliary loads dominates as a result of extended periods of idling or immobility near the terminals. Therefore parasitic loads have a significant impact on the emission reduction potential of a hybrid vehicle with a fixed battery capacity. Our simulations indicated that a hybrid truck with 100kW electrical power has the potential to reduce greenhouse gas emissions by about 30% in drayage operation.



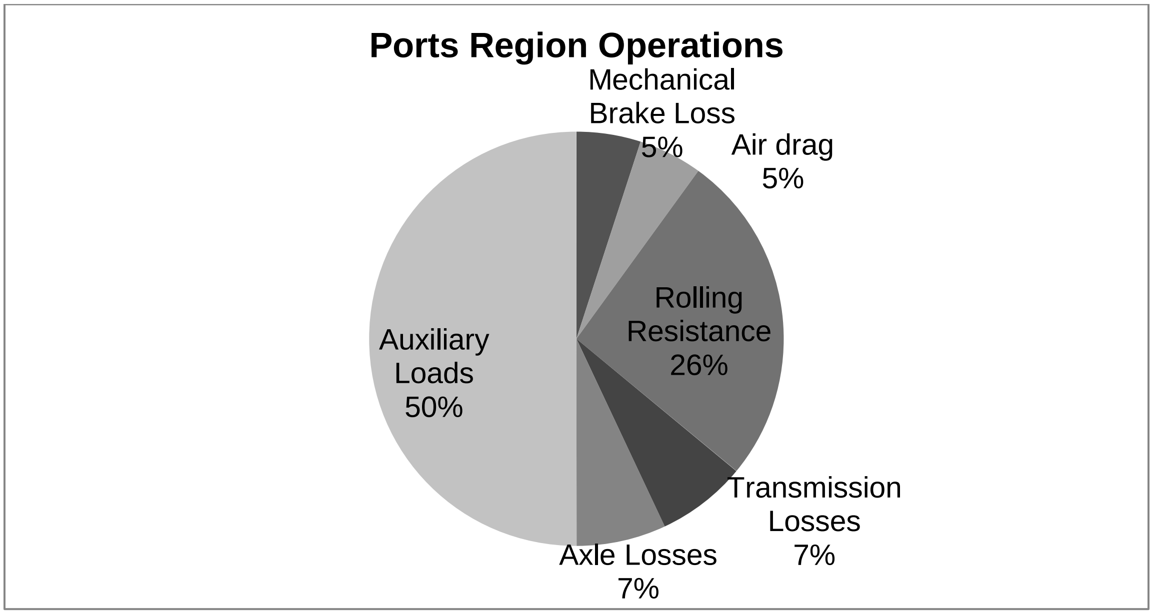


**FIGURE 7 Simulated load distributions on a hybrid-electric truck for a complete drayage cycle and ports region operations.**

## CONCLUDING REMARKS

In this paper a new empirical duty cycle model was developed for real-world drayage operation at the ports of Long Beach and Los Angeles, and incorporates both technical and operational characteristics. The particular focus on drayage operation supports the overarching objective of evaluating Zero / Near Zero Emission Truck technologies to reduce emissions at the ports. Hybrid-electric and electric drivelines present unique constraints in the form of torque and geographical range limits, charging periodicity, etc. Integrating such operational aspects into the duty cycle is therefore imperative to reflect the requirements of the fleet owners and customers in the selection and development of electrification concepts. Historically, duty cycles have been developed for use in an engine dynamometer; therefore, they have to be broken down into smaller components mapped onto torque requirements. Our work thus revealed the need to incorporate several operational aspects to evaluate the performance of advanced vehicle concepts.

Combining the duty cycle model with a vehicle simulator, the hybrid drayage truck load distributions for complete operations and in the ports region were computed. Based on the data collected and a simulation-based analysis, several unique characteristics of drayage operation were identified.  For example, a typical drayage trip consisted of a mix of low and high speeds and/or power operations. The frequency of stopping is high and the duration of stops is unpredictable, thereby making very challenging the sizing of an energy storage unit and its re-charging strategy. While the majority of the trips are within a 20 mile radius, there could be trips almost triple that distance with the additional miles being on highways. Low predictability and repeatability of the duty cycles make it difficult to plan charging infrastructures on the terminals. Evaluating advanced low emissions vehicle concepts on the detailed operational duty cycle presented in this paper yields insights into critical aspects of vehicle design to meet customer requirements. This understanding will eventually mitigate potential barriers to their widescale adoption by the fleets.

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