Development of a Drayage Truck Chassis Dynamometer Test Cycle

Report

FINAL

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1.0 Introduction

The following report describes the development of a chassis dynamometer test schedule for drayage trucks serving the Port of Long Beach and Port of Los Angeles. The underlying data for the current report is based on a previous effort by TIAX to characterize the duty cycle of drayage trucks serving the ports.

2.0 Project Overview

In early 2011, the Port of Long Beach and Port of Los Angeles released a report authored by TIAX that characterizes the duty cycle of on-road, Class 8 drayage trucks at the ports. The report includes statistics based on over 1,000 truck trips collected over a four-week period in late 2010. Based on these statistics, TIAX identifies five modes of operation and an "average" trip associated with each mode. The statistics and trip data from this previous work provide important information on the real-world operation of drayage trucks in the South Coast Air Basin. However, due to certain limitations of chassis dynamometers the trip data collected in the previous work cannot be used directly to conduct chassis dynamometer tests (discussed further in Section 4) that would form the basis for comparable, repeatable testing of different vehicle technologies and configurations (e.g. hybrids, natural gas, battery-electric, etc). This current report describes the development of a test schedule suitable for testing on a chassis dynamometer and based on the modes of operation and trip data previously identified.

3.0 Baseline Data Summary

The reader is encouraged to review the previous report[1], which provides background and base data for the current work. For the sake of brevity, descriptions of the test methods and analytical approaches used in the previous report are not repeated in detail. Instead, the following section summarizes basic drayage operations, the operating modes previously identified, and the trips selected to characterize each mode of operation. These trips form the basis of the chassis dynamometer test mode development described later in this report.

Regions of Operation

Nearly 40% of all containerized goods entering the U.S. move through the Port of Long Beach and/or Port of Los Angeles. The majority of these containers move by drayage truck to a variety of businesses, terminals, warehouses, trans-loading facilities, and container yards in Southern California. Once at these facilities, these goods may then be sent out for delivery to local businesses, loaded onto rail cars, repacked into dry vans, etc. While these facilities are spread out around Southern California, drayage operations are often grouped into three categories based on the first-move distance[2].

Near-Dock Operation: This type of operation involves very short cargo moves from two to six miles in length, generally originating at the marine terminal. Included within this category are cargo moves to nearby container yards or the Intermodal Container Transfer Facility (ICTF), which functions as the Union Pacific rail terminal.

[1] http://www.cleanairactionplan.org/civica/filebank/blobdload.asp?BlobID=2515

[2] First-move distance represents the distance the cargo is moved from the port terminal to another facility or terminal before the cargo is loaded or unloaded from the truck.

Local Operation: A high concentration of warehouses and truck terminals, as well as a major rail yard (Hobart), exist within 20 miles of the ports. These terminals include distribution centers in downtown Los Angeles, Compton, and Rancho Dominguez. For the purposes of the current project, local operation is defined as cargo moves originating or terminating at the ports and having the other end point of the move between six and twenty miles distant from the ports.

Regional Operation: At distances greater than twenty miles from the ports, large warehouse facilities are common and may be used to transfer goods for interstate delivery. Under the current project, regional operation is described as cargo moves between 20 and 120 miles in length. This effectively covers drayage operations to the Mexico border to the south, Coachella Valley to the east, and Bakersfield to the north.

Drayage truck operations in these regions are ultimately the result of a combination of the operating modes described below.

Operating Modes

A vehicle's "mode" of operation is a characterized by its response to certain driving behaviors, usually as a result of similar driving conditions. For example, "Creep" mode is typically considered to be associated with vehicle operation in queue lanes. This mode is typified by long periods of idle, interrupted by brief accelerations and decelerations as the truck moves forward in a queue lane. The most common modes of operation and their characteristics vary between vocations; e.g. common operating modes in a vocation like long-haul trucking are likely to be different from the common modes of operation in drayage. Therefore, trip data recorded in the previous duty cycle characterization effort were analyzed to identify modes of operation specific to drayage operation and each trip was associated with a particular mode of operation. Trip modes were identified by comparing the various statistical parameters identified in Table 1, below. Each trip was then associated with a particular mode of operation and named based on the type of operation the mode appears to represent.

Table 1. Statistical Parameters Calculated for each Trip.

Trip Parameter	Units
Average Vehicle Speed	MPH
Maximum Vehicle Speed	MPH
Total Duration	Seconds
Non-Idle Duration	Seconds
Percentage of Time at Idle	%
Total Engine Output Energy	HP-hr
Average Engine Speed	RPM
Number of Stops	None
Total Distance	Miles
Engine Output Energy per Mile	HP-hr/mile

<u>Creep</u> – Very low speed operation, typical of operation in truck queues.

<u>Low Speed Transient</u> – Low speed operation, typical of on-dock movement.

<u>High Speed Transient</u> –Operation that achieves high peak speeds but does not sustain these speeds. This operation is typical of travel on regional roads, driving in traffic or brief travel on freeways.

High Speed Cruise – High speed operation with sustained high speeds, typical of travel on freeways.

It was determined that the vast majority of Creep and Low Speed Transient data represented queuing or on-dock movements. Therefore, all cargo moves that represented near-dock, local, or regional drayage operation must be High Speed Transient or High Speed Cruise mode trips. Further, nearly all trips greater than 20 miles in length were identified as High Speed Cruise trips. This meant that while most operating modes could be associated with a particular region of operation, the High Speed Transient mode represented trips from two to 20 miles in length; essentially spanning the near-dock and local haul regions of operation. To better characterize near-dock and local haul operations, the High Speed Transient trips were further segmented by trip distance, creating two distinct modes of operation: Short High Speed Transient and Long High Speed Transient. These two modes represent High Speed Transient trips of less than or equal to six miles and greater than six miles in length, respectively.

The subdivision of the High Speed Transient mode into two separate modes produces a total of five modes of operation; 1) Creep, 2) Low Speed Transient, 3) Short High Speed Transient, 4) Long High Speed Transient, and 5) High Speed Cruise.

Average Mode Profiles and "Typical Trips"

Table 2 summarizes the average profiles calculated for each trip mode and the profile of the trip that best fits each mode. The degree of fit for each trip is calculated from the "mean system error" of each trip compared to the mode average. This approach is described in detail in the previous report. Each best-fit trip is assumed to represent a "typical trip" for its mode of operation. The characteristics of these best-fit trips are critical as they are used as the basis of the chassis dynamometer test modes. Figure 1 provides graphical representations of each best-fit trip.

Table 2. Average Mode Profiles and Best Fit Trip Statistics for each Operating Mode.

Mode	Average Speed (MPH)	Maximum Speed (MPH)	Energy per Mile (HP-hr/mile)	Distance (miles)	Stops
Creep	2.65	4.81	8.41	0.03	3.24
Best Fit Trip	2.5	4.9	9.1	0.03	3
percentage of mode profile parameter[3]	**96%**	**102%**	**109%**	**84%**	**92%**
Low Speed Transient	7.64	16.47	4.79	0.58	8.54
Best Fit Trip	6.7	17	4.9	0.59	10
percentage of mode profile parameter	**88%**	**103%**	**102%**	**102%**	**117%**
Short High Speed Transient	17.09	41.33	3.75	4.18	16.18
Best Fit Trip	15.3	40.6	3.7	4.99	16
percentage of mode profile parameter	**90%**	**98%**	**99%**	**119%**	**99%**
Long High Speed Transient	18.74	47.67	3.83	11.29	29.00
Best Fit Trip	19.6	46.5	4.2	8.09	27

[3] Compares the value of the identified parameter to the mode average value. For example, the average number of stops for all Creep mode trips is 3.24. The "best fit" Creep mode trip includes 3 stops and is, therefore, 92% of the average number of stops for this mode.

Mode	Average Speed (MPH)	Maximum Speed (MPH)	Energy per Mile (HP-hr/mile)	Distance (miles)	Stops
percentage of mode profile parameter	**105%**	**98%**	**110%**	**72%**	**93%**
High Speed Cruise	37.93	58.59	3.91	50.59	22.71
Best Fit Trip	38.9	58.5	3.5	48.40	19
percentage of mode profile parameter	**102%**	**100%**	**89%**	**96%**	**84%**

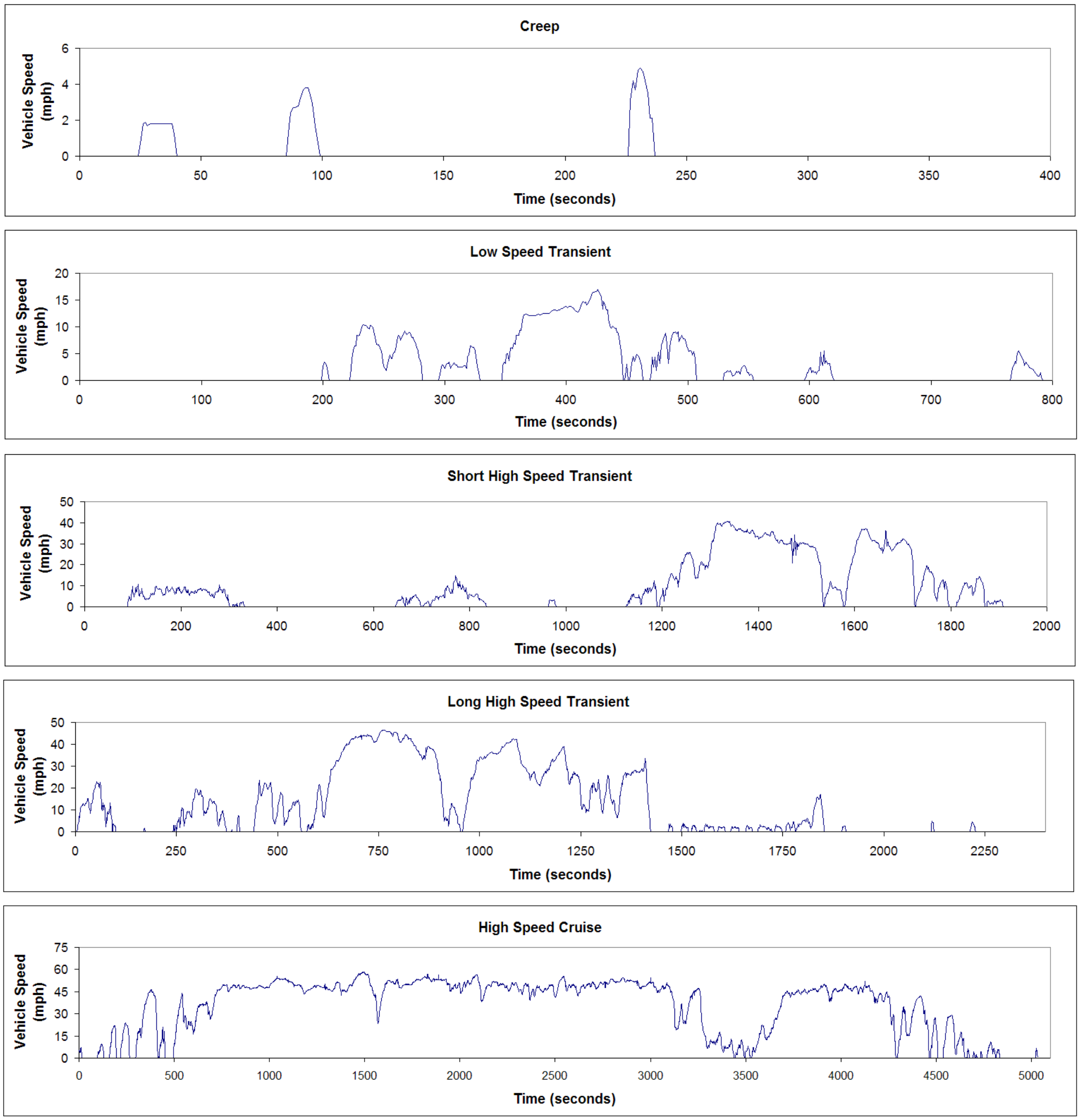

Figure 1. Vehicle Speed vs. Time Data for "Best Fit" Trips Selected for Each Mode of Operation.

4.0 Creating Test Schedule Cycles from Trip Data

The duty cycle data described above provide the ports with a means of describing the average operation of a drayage truck. While this information is useful to vehicle manufacturers in understanding the characteristics of drayage truck operation, the duty cycle data does not necessarily constitute a basis for comparing emissions amongst different vehicle configurations. Therefore, several options were explored to create an emissions test schedule for drayage trucks at the San Pedro Bay Ports. These options included 1) direct use of the duty cycle data, 2) modifying existing duty cycle data through filtering, and 3) modifying existing duty cycle data by replacing portions of the data with other, similar data.

The most straightforward method to produce vehicle speed versus time data for use in a chassis dynamometer test schedule would be to use the real trip data shown in Figure 1, above. However, several issues exist with this approach. First, the real trip data includes deceleration rates that are difficult or impossible to simulate on a chassis dynamometer. Second, high frequency dithering of vehicle speed (small oscillations of vehicle speed when the vehicle is traveling at a near constant speed) in the trip data can be difficult to consistently repeat in a test environment. Inaccurate reproduction of this high frequency dithering can result in large differences between test runs as the error accumulates over the duration of the test cycle. Finally, trip data for three of the five modes are approximately 2,000 seconds or longer in duration. Longer test cycles increase testing costs and the difficulty in properly and repeatably performing the test. Therefore, it is reasonable to establish the goal to reduce the test cycle duration as much as possible without compromising the ability of the test cycle to reasonably represent the operating mode.

The first two issues, high decelerations and high frequency dithering, were addressed by smoothing the data. Smoothing was achieved by filtering the data using a second order Savitzky-Golay smoothing filter[4]. This methodology is equivalent to locally fitting a second order polynomial to a central data point and a specified number of adjacent data points. This filtering method tends to preserve features of the data set better than a running average while providing a degree of smoothing.

The third issue, long duration trip data, was addressed by selective elimination and replacement of segments of the trip data with other test cycle data that were statistically similar, but shorter. This method of "compositing" test cycles was applied only to the High Speed Cruise mode as it was the only mode significantly longer than 2,000 seconds.

Generation of the Composite High Speed Cruise Cycle

Several methods of reducing the duration of the High Speed Cruise trip data were considered including:

1. Utilizing a qualitatively similar existing test cycle such as the Heavy Heavy Duty Diesel Truck (HHDDT) Cruise mode[5].
2. Selecting a new "best fit" trip for the High Speed Cruise mode with a restriction on trip duration.

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[4] A. Savitzky and M. Golay, *Journal of Analytical Chemistry*, vol. 36, pp. 1627 (1964)

[5] Gautam et. al. *Development and Initial Use of a Heavy-Duty Diesel Truck Test Schedule for Emissions Characterization*, SAE Technical Paper 2002-01-1753, 2002

3. Replacing a portion of the High Speed Cruise trip data with an existing test cycle similar to the segment of trip data being replaced.

Any of the above methods will result in a new set of vehicle speed data that is different from the best-fit trip. Therefore, each of these methods was statistically compared to the original trip data using several intrinsic parameters. Table 3 summarizes the statistics calculated for four candidate cycles and the original High Speed Cruise cycle (after applying the Savitzky-Golay smoothing filter as described above). Note that the candidate cycles were selected based on a review of existing test cycles known in literature, as well as a review of the data used to select the original best-fit trips. The candidate cycles listed in Table 3 were constructed as follows:

> ***HHDDT – Cruise***: the unmodified Cruise test mode from the HHDDT test schedule. Equivalent to method 1, described above.
>
> ***HSC – Composite***: the original High Speed Cruise trip data, altered by replacing the majority of the cruise portion of the trip with the HHDDT Cruise mode. Equivalent to method 3, described above.
>
> ***Trip O140_027 and Trip OX49_386***: two trips, collected during the previous duty cycle characterization effort, which are the most statistically similar to the original High Speed Cruise trip. Equivalent to method 2, described above.

The total error for each cycle was calculated by summing the percentage difference for each parameter from the HSC-Smoothed cycle value. Based on this analysis the HSC-Composite candidate cycle was identified as statistically most similar to the baseline cycle. Note that because the HHDDT Cruise cycle is shorter in duration and distance travelled than the segment of the High Speed Cruise cycle being replaced, data from the HHDDT Cruise portion of a chassis dynamometer test run must be scaled up before calculating total emissions or fuel consumption.

Table 3. Comparison of Methods to Reduce High Speed Cruise Trip Duration.

Statistic	Units	HSC-Smoothed (baseline)	HHDDT - Cruise	HSC – Composite	Trip O140_027	Trip OX49_386
Average Speed Ex-Idle	MPH	38.4	43.2	35.9	37.2	35.2
Max Speed	MPH	58.5	59.3	59.3	57.1	57.8
Max/Average Speed		1.52	1.37	1.65	1.54	1.64
Avg. Kinetic Energy Ex-Idle	(MPH)^2	867	1124	875	837	778
Average Acceleration	MPH/sec	0.35	0.26	0.38	0.44	0.51
Average Deceleration	MPH/sec	-0.46	-0.28	-0.45	-0.52	-0.60
Total Error			**41%**	**19%**	**22%**	**42%**

It is anticipated that, in the near term, drayage trucks being tested under the port drayage test schedule will also be tested under the HHDDT. By replacing a portion of the High Speed Cruise test cycle with the HHDDT Cruise cycle, the test lab can perform the HHDDT Cruise cycle independently of the other portions of the High Speed Cruise test cycle and mathematically reconstruct the complete test cycle. In cases where the HHDDT test schedule is not performed in conjunction with the port drayage test schedule, it may still be advantageous to the test lab to perform the HHDDT Cruise test cycle separately from the other portions of the High Speed Cruise cycle. This approach would prevent the test lab from being required to conduct the entire 3,095 seconds of High Speed Cruise cycle without interruption.

Drayage Truck Test Schedule

Figure 2 depicts the test cycles that result from applying the above described methodology. While five test cycles are shown, in practice there will likely be seven distinct test cycles. The HHDDT cruise portion (shown in red) of the High Speed Cruise cycle is likely to be performed separately from the other two segments (shown in blue), thus creating a sixth test cycle. The seventh cycle is an idle mode cycle required to calculate emissions and fuel consumption rates at steady-state idle.

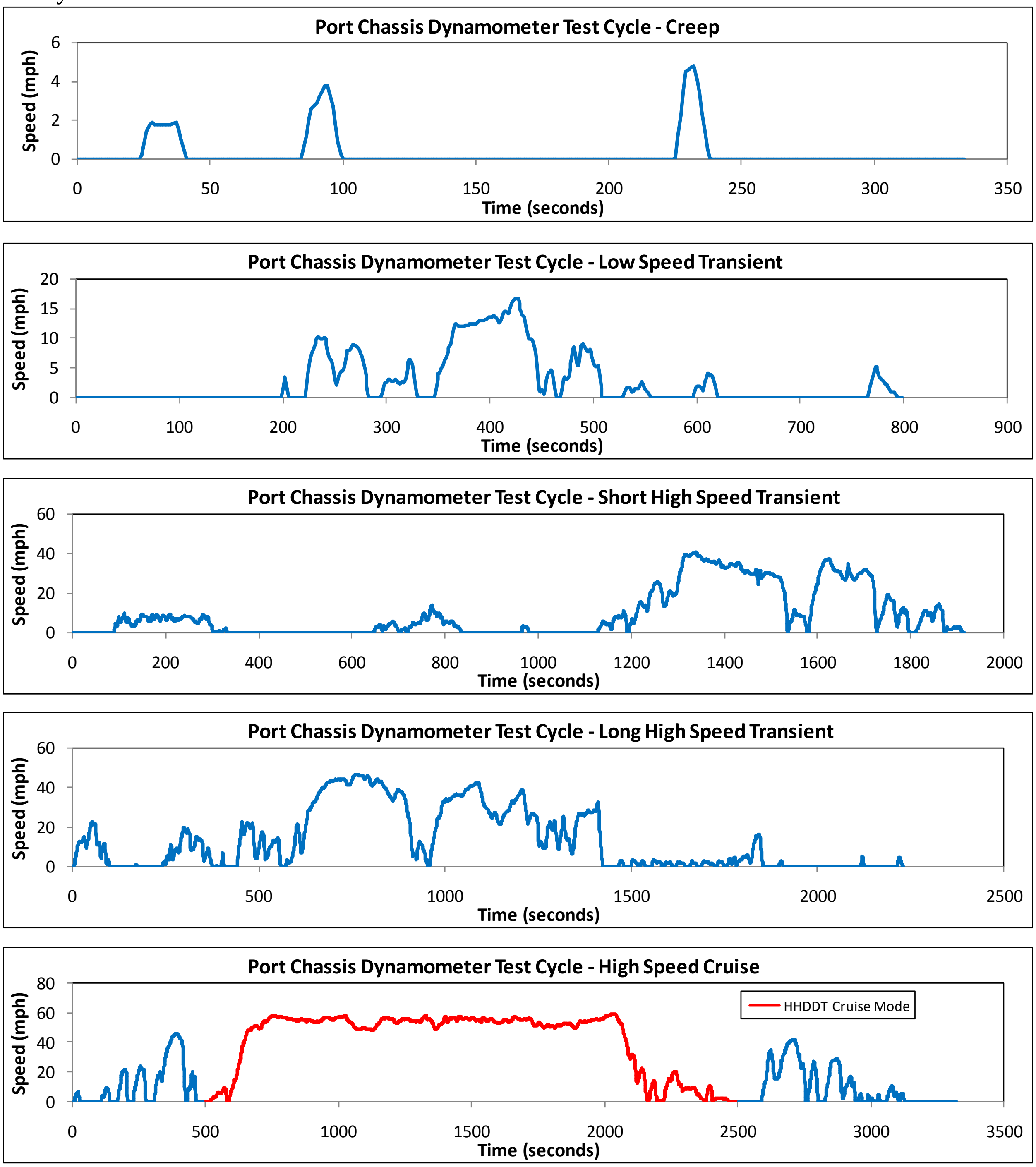

Figure 2. Cycles Comprising the Drayage Truck Chassis Dynamometer Test Schedule.

The idle mode cycle should be a minimum of 15 minutes in duration. It is anticipated that this duration will be sufficient to collect a measurable NOx sample. The duration of the idle period may be extended to collect measurable NOx samples, as needed.

As this test schedule has not yet been demonstrated on a chassis dynamometer, no information exists regarding the effect of specific test procedures on the repeatability or accuracy of emissions and fuel consumption. Therefore, TIAX recommends that the test lab follow the same general procedures, including vehicle warm up and intercycle test times as those described in the HHDDT test schedule. Additionally, cycles should be tested in order, beginning with the idle mode test cycle, proceeding to the Creep cycle, followed by the transient cycles in order of cycle length. Finally, the High Speed Cruise cycle should be tested. If the HHDDT Cruise portion of the High Speed Cruise cycle is to be tested separately, then the first and third segments of the High Speed Cruise cycle should be tested before the HHDDT Cruise segment. This series of tests is listed below.

Order of test cycles (assumes a segmented High Speed Cruise cycle test)

1. Vehicle warm-up
2. Idle Mode
3. Creep Mode
4. Low Speed Transient Mode
5. Short High Speed Transient Mode
6. Long High Speed Transient Mode
7. High Speed Cruise Mode (Segments 1 and 3)
8. High Speed Cruise Mode (Segment 2, i.e. HHDDT Cruise portion)

5.0 Construction of Modal and "Region of Operation" Data from Test Schedule Data

Once emissions and fuel consumption data have been gathered under Drayage Truck Test Schedule, these data must be appropriately combined and scaled to produce emissions and fuel consumption estimates for the key regions of operation that are the original focus of the ports. In particular, the results of the test schedule should provide emissions estimates in grams per trip for near-dock, local, and regional operations. While the original duty cycle development effort identified the combination of modes that are representative of each type of operation, these modes have been modified to create practical test cycles. To calculate emissions for the underlying mode of each test cycle, it is necessary to account for the elimination of idle data in all cycles and compositing of the High Speed Cruise cycle. This process is graphically depicted in Figure 3 below.

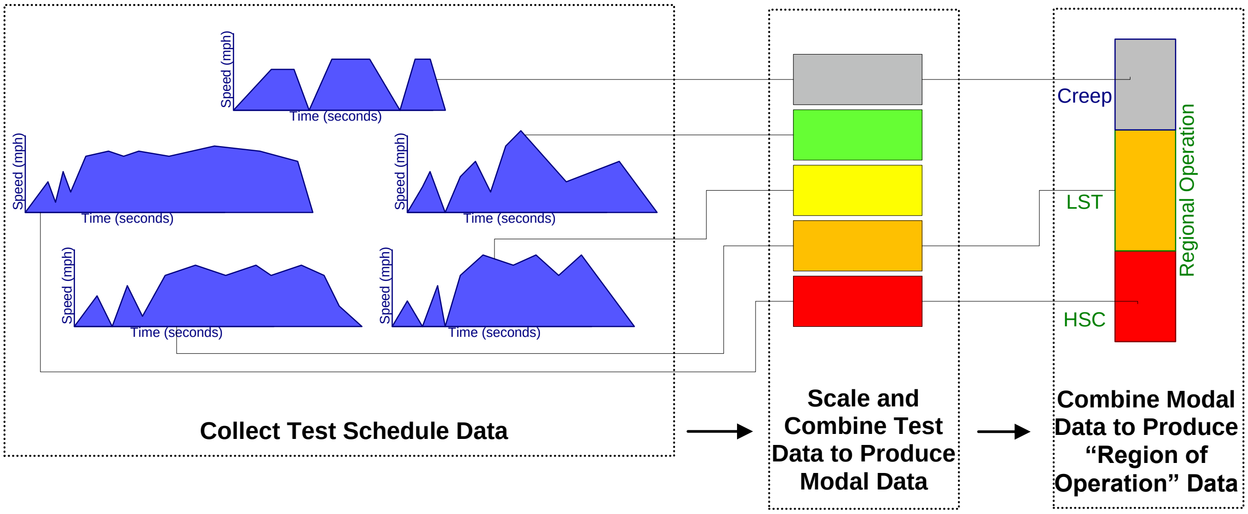

Figure 3. Process of Creating Operating Region Emissions Estimates from Test Schedule Data.

Table 4 summarizes the trip data for each mode and the scaling required by the composited High Speed Cruise segment.
In the case of the High Speed Cruise mode, the test cycle required the use of the HHDDT Cruise mode to replace a portion of the High Speed Cruise data that is longer in duration and miles travelled. Because this particular segment of trip data is predominantly steady-state, high-speed operation, the emissions and fuel consumption are generally proportional to the distance travelled. Therefore, emissions collected during High Speed Cruise Segment 2 are scaled up based on the ratio of the distances of the original segment and the HHDDT Cruise segment. This ratio is 1.941.

Table 4. Changes Made to Modal Trip Data to Produce Test Cycles.

Mode	Mode Length (seconds)	Required Scaling of emissions data
Creep	335	n/a
Low Speed Transient	799	n/a
Short High Speed Transient	1,915	n/a
Long High Speed Transient	2,231	n/a
High Speed Cruise Segment 1	497	n/a
High Speed Cruise Segment 3	743	n/a
High Speed Cruise Segment 2 (HHDDT-C)	2,083	Scale up by 194.1%

Once emissions and fuel consumption have been calculated for each mode, the modal data should be combined to produce estimates for each operating region. The previous characterization of port duty cycles found that each duty cycle consists of a high speed mode (either Transient or Cruise) preceded by one Creep-mode and one Low Speed Transient mode trip. In all cases, the same Creep and Low Speed Transient trips are used and these are the best-fit trips identified previously. Based on the distribution of trips by trip length and mode, duty cycles are constructed as follows:

Near-dock (2 to 6 miles) – Creep → Low Speed Transient → Short High Speed Transient
Local (6 to 20 miles) - Creep → Low Speed Transient → Long High Speed Transient

Regional (20+ miles) - Creep → Low Speed Transient → High Speed Cruise

After the total mass emissions for each pollutant in each region of operation are calculated, these values should be divided through by the total trip length in the corresponding region of operation. This will produce values in units of grams per mile and are the primary figures of merit produced from the Drayage Truck Test Schedule. It should be kept in mind that these figures form a repeatable basis of comparison for various vehicles in drayage service. These figures do not necessarily reflect the actual in-use emissions of drayage trucks. As such, the results of these tests should not be used for emissions inventory purposes without additional research.

5.0 Discussion and Recommendations

The chassis dynamometer test cycle described by this report is intended to provide the Port of Long Beach and Port of Los Angeles with a tool to compare the emissions performance from various drayage truck technologies. While this cycle has been developed using actual in-use vehicle data and methods similar to those used to develop the HHDDT test cycle, the current cycle has not benefitted from any sort of validation on a chassis dynamometer. Such testing would verify that the port chassis dynamometer test cycle can reasonably be executed and that the results are repeatable. Therefore, it is recommended that:

- The drayage truck chassis dynamometer test cycle described in this report be performed on a Class 8 semi-tractor that is similar in characteristics to the current drayage fleet. As the fleet is predominantly diesel, it is recommended that the truck be equipped with a diesel engine with a horsepower rating in the 400-500 HP range.
- Results from the test should include a review of the repeatability of fuel consumption and emissions data, as well as the ability of the test driver to follow the test cycle.
- Pending successful verification testing as described above, it is recommended that the ports establish baseline emissions data for diesel and LNG trucks that are representative of the current drayage fleet.

Currently, the South Coast Air Quality Management District is preparing to conduct emissions testing on several heavy duty vehicles, including diesel and LNG drayage trucks. If the ports elect to participate in this testing by including the drayage truck test cycle, the ports will have the opportunity to generate the aforementioned baseline data as well as compare the results of the drayage truck test cycle to other existing cycles like the UDDS and HHDDT.