

# EPA GHG Certification of Medium- and Heavy-Duty Vehicles: Development of Road Grade Profiles Representative of US Controlled Access Highways

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## ABSTRACT

In collaboration with the U.S. Environmental Protection Agency and the U.S. Department of Energy, the National Renewable Energy Laboratory has conducted a national analysis of road grade characteristics experienced by U.S. medium- and heavy-duty trucks on controlled access highways. These characteristics have been developed using TomTom's commercially available street map and road grade database. Using the TomTom national road grade database, national statistics on road grade and hill distances were generated for the U.S. network of controlled access highways. These statistical distributions were then weighted using data provided by the U.S. Environmental Protection Agency for activity of medium- and heavy-duty trucks on controlled access highways. The national activity-weighted road grade and hill distance distributions were then used as targets for development of a handful of sample grade profiles potentially to be used in the U.S. Environmental Protection Agency's Greenhouse Gas Emissions Model certification tool as well as in dynamometer testing of medium- and heavy-duty vehicles and their powertrains.

**CITATION:** Wood, E., Duran, A., and Kelly, K., "EPA GHG Certification of Medium- and Heavy-Duty Vehicles: Development of Road Grade Profiles Representative of US Controlled Access Highways," *SAE Int. J. Commer. Veh.* 9(2):2016, doi:10.4271/2016-01-8017.

## INTRODUCTION AND BACKGROUND

In August of 2011, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration adopted a national program to reduce greenhouse gas (GHG) emissions and improve fuel efficiency of medium-duty (MD) and heavy-duty (HD) trucks [1, 2, 3, 4]. In February of 2014, President Obama announced efforts to update MD/HD vehicle regulations in Phase 2 of EPA's national GHG program [5, 6].

As part of the EPA's proposed Phase 2 rulemaking, the U.S. Department of Energy (DOE) and EPA are partnering to support a targeted project to refine and evaluate appropriate duty cycles for tractor-trailers and vocational vehicles to be used as part of MD/HD vehicle certification procedures for GHG emission standards. The National Renewable Energy Laboratory (NREL) will provide technical leadership for this work, utilizing DOE-supported data, tools, and expertise.

In particular, this paper documents work done to characterize nationally representative road grade profiles for certification testing and simulation on highway drive cycles. Current EPA highway cruise drive cycles are performed at constant speeds of 55 and 65 miles per hour (mph) with zero road grade. The goal of this project was to develop and identify road grade profiles that are representative of U.S. controlled access highways.

This analysis will generate activity-weighted distributions of road grade and hill length at the national level and propose several potential grade profiles for testing and simulation at highway speeds.

## NATIONAL STATISTICS

The TomTom national road grade database [7, 8, 9] was selected as the primary data source for this analysis based on an NREL evaluation relative to road grade information collected by Southwest Research Institute [10]. Using the TomTom database, a suite of statistical distributions was developed to describe grades experienced by MD/HD trucks on controlled access highways across the United States. This suite of descriptive statistics is developed using two analytical procedures: 1) quantifying the percent of national roadway distances at grade, and 2) evaluating national highway topography by segmenting roadways into a series of "half hills" and recording statistics such as distance, average grade, and maximum grade for each segment. Finally, activity weighting is applied to account for the national distribution of MD/HD vehicle highway traffic.

As this analysis is intended to support highway testing procedure, the U.S. highways to be examined are presented. Figure 1 shows a map of the U.S. overlaid with controlled access roads per the TomTom road network. This includes the U.S. interstate system in addition to a number of locally controlled access highways.

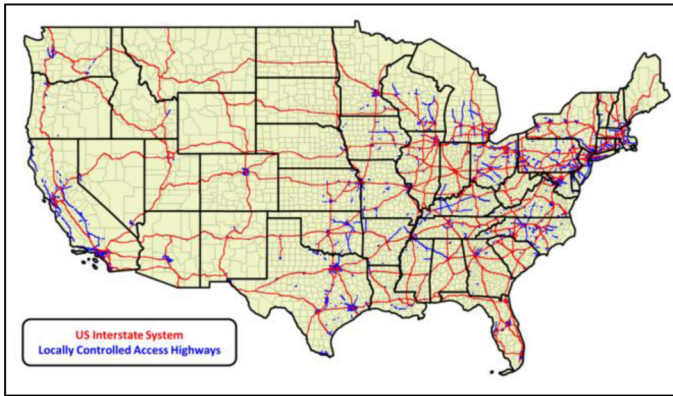


Figure 1. TomTom MultiNet map of U.S. controlled access highways.

We would also like to understand if road grade distributions feature significant variation when segmented by truck speed limits to align data generated in this report with EPA's existing 55- and 65-mph constant-speed drive cycles. The same U.S. controlled access highways were segmented by state-defined truck speed limits per TomTom's Logistics data layer [11]. While truck classifications can vary by state, vehicles subject to truck speed limits generally fall in weights classes 7-8, feature gross vehicle weight ratings of over 26,000 pounds, and have three or more axles.

Figure 2 shows a breakdown of U.S. controlled access highway miles by truck speed limit and by U.S. Census Urban Area boundaries. From this plot, we see that the majority of U.S. controlled access highway miles come from routes with truck speed limits from 55 to 75 mph. Roadways with truck speed limits less than 55 mph are discarded on the basis that vehicle operation on such roads would likely be occurring in congested urban areas and would not be constant speed. Roadways with truck speed limits greater than 75 mph are discarded on the basis that these only occur in a very small area of the country and do not appear to be representative of national roadways, and their omission would not have a meaningful effect on the results. Therefore, the remainder of this analysis will focus on roadways in the five truck speed limit bins shown in Figure 2.

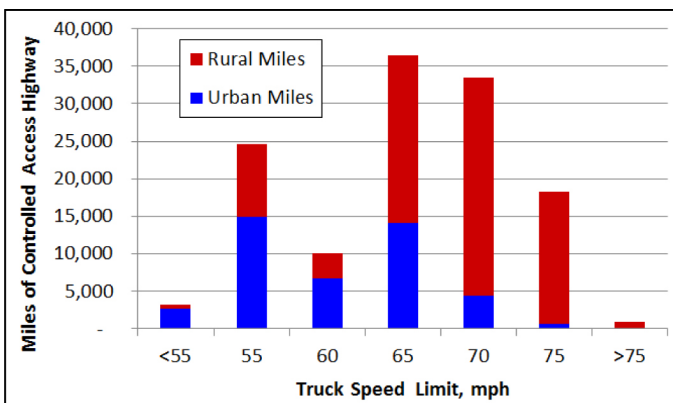


Figure 2. Mileage breakdown of U.S. controlled access highways by truck speed limit and U.S. Census urban area designation

### Road Grade by Distance Analysis

The TomTom Advanced Driving Attributes road grade database was queried for all U.S. controlled access roads at uniform 52.8-foot intervals (100 points per mile) using linear interpolation. This procedure quantifies the percent of national highway distance at grade. Given that there are approximately 127 thousand miles of U.S. controlled access highway, these calculations result in generation of approximately 12-million road grade measurements. The data are aggregated by five truck speed limits and 1,728 U.S. counties with controlled access highways to produce 8,640 distributions of grade by distance.

Figure 3 plots the data as cumulative distributions for all 1,728 U.S. counties in question (grade by truck speed limit is summed by county for this plot). While the density of data on this plot provided little in the form of analytical value, it is informative to understand the dramatic variability in road grade experienced by trucks in different regions of the country.

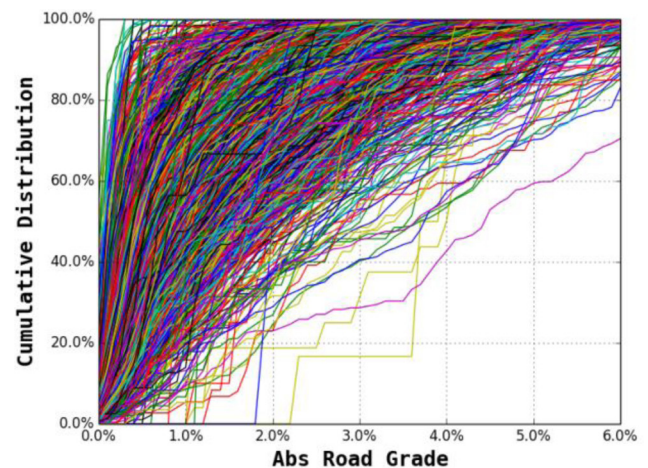


Figure 3. Cumulative distributions of road grade by distance for 1,728 U.S. counties

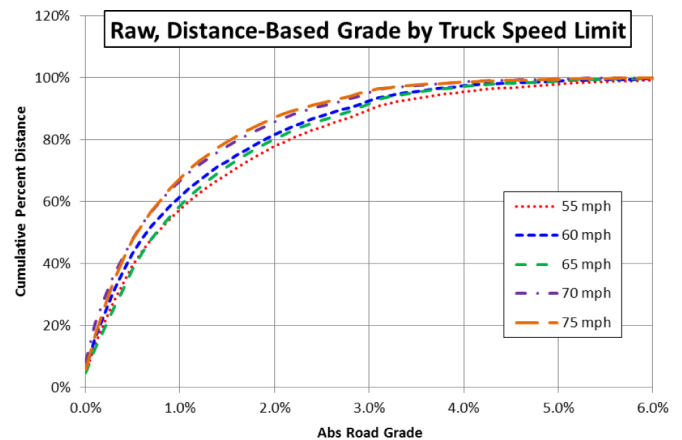


Figure 4. Raw distance-based cumulative distribution of absolute road grade by truck speed limit

In Figure 4, the 8,640 distributions are summed by truck speed limit with all data points having equal value within each truck speed limit segment (effectively resulting in distance weighting). A trend emerges from this plot that roadways with high truck speed limits generally have lower concentrations of road grade relative to roadways with low truck speed limits. For example, approximately 78% of distances on highways with truck speed limits of 55 mph exhibit less than 2% absolute road grade. That figure jumps to approximately 87% for highways with truck speed limits of 75 mph.

### Half Hill Analysis

While querying the national road grade database by distance is informative, additional information can be gleaned. Our second round of analysis consisted of evaluating national highway topography by segmenting roadways into a series of “half hills” and recording statistics for each segment.

A half hill in this analysis was defined as a continuous stretch of roadway where grade does not change sign (i.e., sections of exclusive climb or descent). Figure 5 shows this half hill segmenting where a 13-mile stretch of controlled access highway is subdivided into 16 unique half hills (eight climbs and eight descents). A number of statistics are recorded for each identified half hill, including distance, average grade, and maximum grade (minimum grade for segments of descent). This processing routine is applied to the entire U.S. controlled access highway system and results in generation of statistics for approximately 220 thousand half hills nationwide.

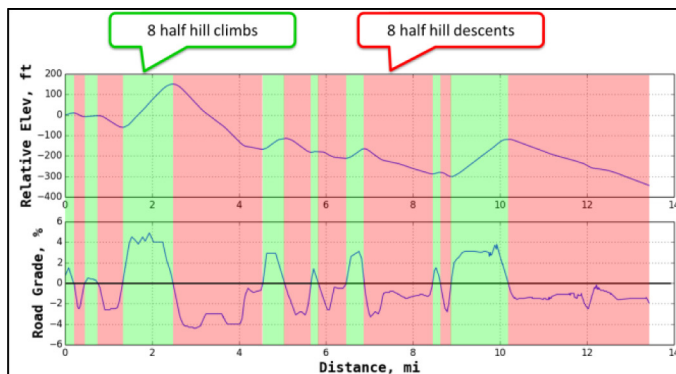


Figure 5. Example section of controlled access highway broken into 16 half hills (eight climbs and eight descents)

Figure 6 plots raw distance-based cumulative distributions of half hill distance by truck speed limit. Similar trends in half hill distances are apparent for roads with truck speed limits between 55 and 70 mph. However, half hill distances are noticeably longer on roads with truck speed limits of 75 mph. For example, approximately 70% of roadway distances on routes with 75-mph truck speed limits occur on half hills of 2 miles or less. That figure jumps to a range of 82%-87% for routes with truck speed limits of 55 to 70 mph.

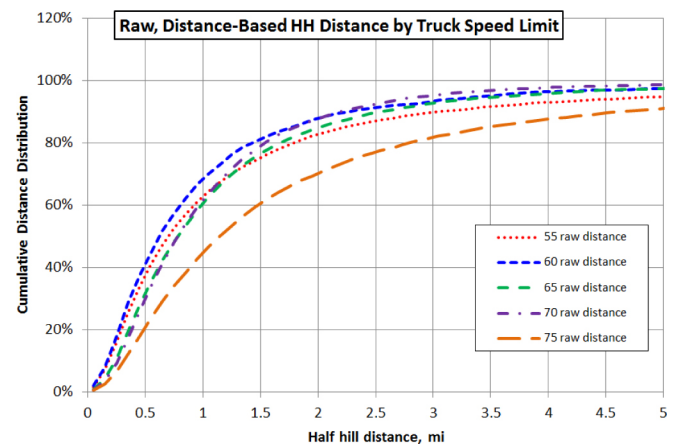


Figure 6. Raw distance-based cumulative distributions of half hill (HH) distance by truck speed limit

Figure 7 shows national half hill data plotted by scattering maximum grade (minimum grade for segments of descent) against average grade for each half hill. The red dashed diagonal line indicates half hills where maximum and average grade are nearly equal. Overall, we find an average grade ratio (maximum divided by average half hill grade) of 1.76.

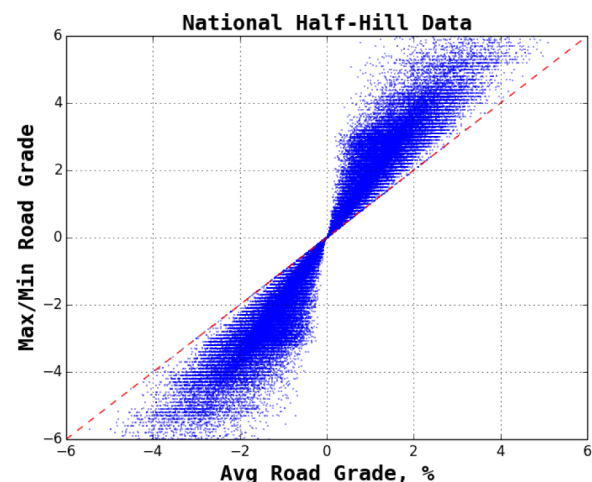


Figure 7. Maximum (or minimum) versus average road grade for all measured half hills. Red dashed diagonal line shows where maximum and average grade are nearly equal.

### Activity-Weighted Values

Activity data for MD/HD trucks are sourced from EPA’s Motor Vehicle Emission Simulator (MOVES) database of vehicle miles traveled (VMT) by county. After removing light-duty vehicle activity and VMT from uncontrolled access roads, the remaining activity data from MD/HD vehicles on controlled access roads are plotted in Figure 8. In this subset of the MOVES VMT database, the majority of activity is generated from short- and long-haul combination trucks. These are vehicles likely to fall into weight classes 7-8 and thus are subject to the truck speed limits discussed above.

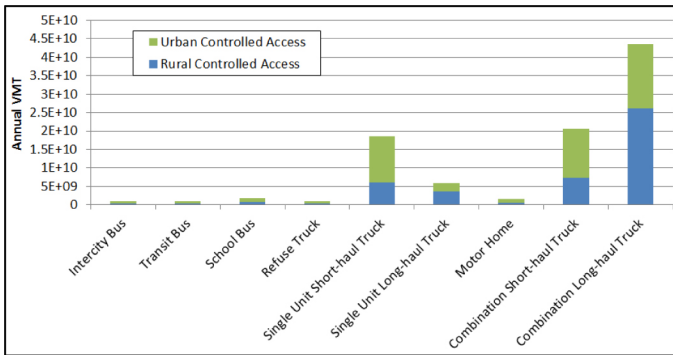


Figure 8. EPA MOVES VMT database for MD/HD vehicles on controlled access roads only

MOVES VMT data for the subset of MD/HD vehicles on controlled access roads are spatially plotted by county in Figure 9 to better understand regional variability with respect to MD/HD truck traffic. This map reveals concentrations of activity in urban centers and on select interstate highway systems primarily oriented in the eastern third of the United States.

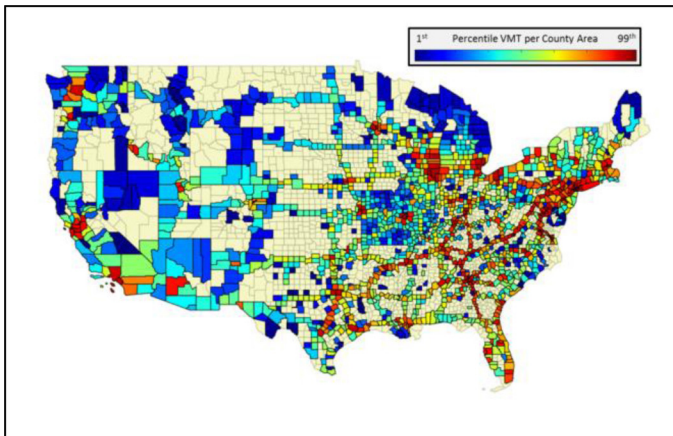


Figure 9. EPA MOVES VMT database mapped by county for MD/HD trucks operating on controlled access roads

Because VMT from the MOVES database only allows resolution at the county level, VMT must be subdivided within each county prior to applying activity weighting. For the analysis of road grade by distance, county MD/HD controlled access VMT are uniformly distributed over queried grade points in a county (points uniformly spaced at 100 points per mile on all controlled access roads within each county). For half hill statistics, weights are generated for every half hill according to Equation 1.

$$w_i = VMT_{county,i} * \left( \frac{d_i}{\sum_{i=1}^{hh_{county,i}} d_i} \right) \quad (1)$$

where  $w_i$  is the individual weight of each half hill,  $VMT_{county,i}$  is the MOVES VMT from the county containing half hill  $i$ ,  $d_i$  is the distance of half hill  $i$ , and  $hh_{county,i}$  is the total count of all half hills

from the county in question. These weights are then used to generate activity-weight distributions of half hill distance as shown in Equation 2.

$$P(d) = \left( \sum_{i=1}^n \begin{cases} d_i < d \\ else \end{cases} w_i \right) / \sum_{i=1}^n w_i \quad (2)$$

To align with existing EPA highway test cycle speeds (55 and 65 mph), the TomTom data from roads with truck speed limits of 55 and 60 mph are grouped into a shared distribution to inform testing at 55 mph. The remaining truck speed limit data for of 65, 70, and 75 mph are grouped into a shared distribution to inform testing at 65 mph. Further future on-road data analysis may help evaluate how closely the fixed 55- and 65-mph test cycle speeds align with actual on-road speeds for each of these road speed limit categories.

With the data now in two groups for EPA test cycles at 55 and 65 mph, the raw and activity-weighted distributions of road grade by distance for the 55- and 65-mph test groups are plotted in Figure 10. Activity-weighted distributions for both test groups closely match the raw data.

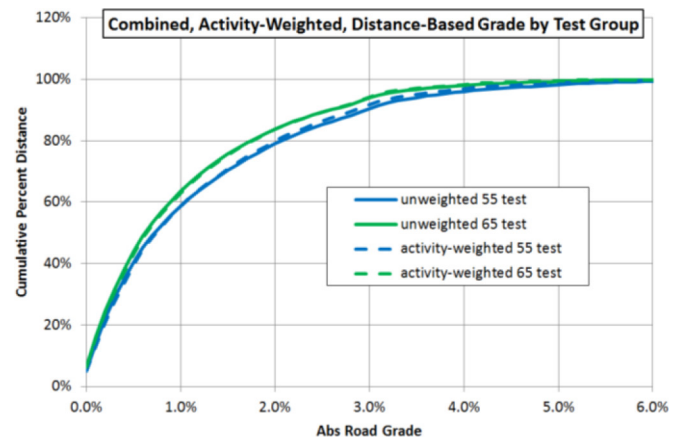


Figure 10. Combined activity-weighted, distance-based cumulative distributions of absolute road grade by target test speed

To demonstrate the statistical difference between the activity-weighted 55-mph and 65-mph test groups, Kolmogorov-Smirnov (KS) hypothesis testing was conducted at a 95% confidence level [12, 13, 14]. Hypothesis testing revealed a KS statistic of 0.046 and a P-value of 0.000, indicating that the two distributions were determined to be statistically unique (i.e., the null hypothesis that the distributions are equivalent was rejected).

Activity-weighted data are also generated for the distance-based distributions of half hill distances, shown in Figure 11. The application of activity weights shifts both the 55- and 65-mph distributions toward shorter half hill distances.