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Identifying Roadway Physical Characteristics that Contribute to Emissions Differences between Hybrid and Conventional Vehicles

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Identifying Roadway Physical Characteristics that Contribute to Emissions Differences between Hybrid and Conventional Vehicles

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract In this study, a second-by-second (SbS) data set obtained from monitoring vehicle emissions over a series of 75 test runs from 2 test vehicles (a conventional vehicle (CV) and a hybrid-electric vehicle (HEV)) over an 18-month period in 2010-2011 during real-world on-road operations on a specified 32-mile route in Chittenden County, Vermont was used in an innovative new method of analysis to assess emissions *differences* between the two propulsion systems and attribute these differences to physical roadway/infrastructure characteristics. The K-S test was used to assess the difference between the cumulative distributions of the CV and HEV emissions samples on each link, and the K-S test statistic was regressed against the full set of roadway link characteristics. The regression results allowed the team to identify specific roadway characteristics that contribute to emissions differences between the vehicle types. Overall, the models that included maximum grade and intersection control type performed best, however speed limit and horizontal curvature were also shown to be important. The performance differences identified in this project confirm that engine controls that are responsive to roadway characteristics are necessary.

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Disclaimer

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NCST

Identifying Roadway Physical Characteristics that Contribute to Emissions Differences between Hybrid and Conventional Vehicles

A National Center for Sustainable Transportation Research Report

April 2019

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Identifying Roadway Physical Characteristics that Contribute to Emissions Differences between Hybrid and Conventional Vehicles

EXECUTIVE SUMMARY

The research described in this report helps researchers and modelers understand the differences between conventional and hybrid-electric vehicle in terms of emissions within different parts of the transportation system. This knowledge will in turn be useful for future programming of smart propulsion vehicles so that their operation can result in minimized emissions and net energy consumption, the latter of significance for electric vehicle range and eco-driving. In this study, a second-by-second (SbS) data set obtained from monitoring vehicle performance and emissions over a series of 75 test runs from 2 test vehicles (a conventional vehicle (CV) and a hybrid-electric vehicle (HEV)) over an 18-month period in 2010-2011 during real-world on-road operations on a specified 32-mile route in Chittenden County Vermont. An innovative new method of analysis allowed the assessment of emissions differences between the two propulsion systems and the attribution of these differences to physical roadway/infrastructure characteristics. The K-S test was used to assess the difference between the cumulative distribution functions (CDFs) of the CV and HEV emissions samples on each link. The application of the K-S test resulted in a hypothesis test result, an asymptotic p-value, and the test statistic, D*.

The test statistic was regressed against the full set of roadway link characteristics. The multi-regression results allowed the team to identify the specific roadway characteristics that contribute to emissions differences between the vehicle types. A step-wise, reductive regression was conducted, with D* as the independent variable and the road link physical characteristics in as the dependent variables:

- Grade (%)
- Speed Limit (mph)
- One-Way Lane + Shoulder Width (ft.)
- Width of the Median (ft.)
- Lanes Each Way
- One-Way Capacity (vph)
- One-Way Daily Capacity (vpd)
- 2010 AADT (both ways) (vpd)
- 2010 AADT/Daily Capacity (both ways)
- Horizontal Curvature (degrees)

To explore the relationship between emissions rates and the 9 intersection-control/turning-movement types at the beginning and end of each link, each of these control types was applied in a cross-classification model. Each control type was cross-classified with the variables from the regression models with the highest t-scores. The average D* was calculated for each cross-classified category and this value was used to calculate a residual for each of the 80 links in the study. From the residual, an R-squared was calculated for each of the cross-classification models.

Results of the final regression models for each of the 7 pollutants, including each estimated coefficient (β), its associated t-score, and the adjusted R-squared of each model, are provided in Table ES-1.

Table ES-1. Results of Final Regression Models

	CO		**CO_2**		**PN**		**BZ**		**NO**		**NO_2**		**HCHO**	
Variable	**β**	**t**	**β**	**t**	**β**	**t**	**β**	**t**	**β**	**t**	**β**	**t**	**β**	**t**
Speed Limit	na		-0.01	-5.97	-0.00	-3.85	-0.01	-6.40	-0.01	-6.18	-0.01	-5.88	-0.01	-6.30
Maximum Grade	-0.01	-2.84	-0.02	-4.75	-0.02	-4.68	-0.02	-4.84	-0.03	-5.21	-0.02	-4.68	-0.02	-4.61
Horizontal Curvature	-0.01	-2.15	-0.02	-3.64	-0.01	-3.65	-0.02	-3.74	-0.02	-4.02	-0.01	-3.63	-0.02	-3.61
Constant	0.50	36.1	0.90	16.1	0.56	13.0	0.89	16.0	0.87	16.4	0.76	15.4	0.88	16.2
Adjusted R-squared	0.13		0.49		0.40		0.51		0.52		0.48		0.49	
na – Speed limit was not found to be significant in the final regression model for CO														

The negative signs on the coefficients of each dependent variable indicate that increasing the magnitude of these coefficients (higher speed limits, steeper grades, and sharper curves) contributes to decreased differences in emissions between the two vehicle types. This finding confirms that the greatest emissions differences occur when the CV and HEV vehicles are least challenged by the physical infrastructure.

Each control type was cross-classified with the strongest variables from the regression models – speed limit and maximum grade. For the cross-classification, speed limit was divided into 2 categories (low and high) and maximum grade was divided into 4 (negative, flat, low positive, and high positive). The average D* was calculated for each cross-classified category and this value was used to calculate a residual for each of the 80 links in the study. From the residual, an R-squared was calculated for each of the cross-classification models and compared to the R-squared for the regression models, as shown in Table ES-2.

Table ES-2. R-squared values for the cross-classification models and regression models

	Cross-Classification Models		Multi-Regression Models (Table ES-1)
Emission Type	**Speed Limit x Control Type**	**Max Grade x Control Type**	**Speed Limit, Max Grade, and Horizontal Curvature Regression**
CO	0.25	0.36	0.13
CO_2	0.44	0.62	0.49
PN	0.37	0.57	0.40
BZ	0.46	0.66	0.51
NO	0.44	0.64	0.52
NO_2	0.44	0.65	0.48
HCHO	0.45	0.65	0.49

Overall, the cross-classified model with maximum grade and control type performed best, based on R-squared values from 0.36 to 0.66. The results in Table ES-2 indicate that the combination of intersection controls and turning movements at each end of the link is significant in determining emissions differences between the two vehicle types. Control types 1, 2, and 6 led to the highest values of D*, indicating differences in emissions between the CV and HEV vehicle types where links have:

1. Stop-Sign/Turn to Stop-Sign/Turn
2. Thru-Signal to Stop-Sign/Turn
6. Thru-Signal to Thru-Signal

This finding indicates that the effect of traffic controls must also be considered when modeling the effect of roadway infrastructure on SbS emissions from CVs vs HEVs.

The performance differences identified in this project confirm that engine-switching controls that are responsive to roadway characteristics are necessary. It should also be recognized that the results have direct implications for fuel consumption by electrified vehicles due to the results obtained here for CO_2 (CO_2 and fuel consumption being closely related via mass balance). However, future research is needed to refine the mapping of roadway characteristics to emission rates under a variety of engine control strategies for HEVs. It is not clear what control strategies for a HEV ICE would reduce emissions the most as these roadway characteristics are encountered. Additional research can seek to modify the control strategies between a strategy that is optimized for performance (without regard to roadway characteristics), a strategy that is optimized for fuel economy (without regard to roadway characteristics), and a strategy that is optimized to minimize emissions by responding to the oncoming roadway characteristics. This type of evaluation will provide definitive evidence of the need for responsiveness to the roadway characteristics, as well as providing an initial understanding of specific engine-control strategy needed to control the propulsion of a HEV to reduce emissions and fuel consumption.

Introduction

The research described in this report helps researchers and modelers understand the differences between conventional and hybrid-electric vehicles in terms of emissions within different parts of the transportation system. This knowledge will in turn be useful for future programming of smart propulsion vehicles so that their operation can result in minimized emissions and net energy consumption, the latter of significance for electric vehicle range and eco-driving. This report summarizes research findings that are detailed in an upcoming journal article.

In this study, a second-by-second (SbS) data set obtained from monitoring vehicle performance and emissions over a series of 75 test runs from 2 test vehicles (a conventional vehicle (CV) and a hybrid-electric vehicle (HEV)) over an 18-month period in 2010-2011 during real-world on-road operations on a specified 32-mile route in Chittenden County Vermont. An innovative new method of analysis allowed the assessment of emissions differences between the two propulsion systems and the attribution of these differences to physical roadway/infrastructure characteristics.

The objectives of this research are to improve our understanding of the differences in emission rates associated with the time-varying use of an internal-combustion engine (e.g., full-time use in the CV and part-time use in the HEV) and to relate these differences to physical characteristics of the roadway.

The Kolmogorov–Smirnov (K-S) test, a nonparametric test used to compare two samples, was used to analyze the relationship between emissions differences and roadway physical characteristics. The advantage of the K-S test is that all data contribute to the test result, making it useful for very large datasets like SbS driving data, but the data sets do not need to be paired, nor do their distributional forms need to be identical. The K-S test yields a continuous test statistic that was then used directly to develop regression models of emissions differences for varied physical roadway characteristics. Understanding these differences, and the roadway characteristics that cause them, is critical to the minimization of emissions by autonomous CVs and HEVs.

Background

This study takes advantage of a unique data set consisting of SbS emission rates from two light-duty gasoline passenger cars of the same make and model (Toyota Camry) but different propulsion systems (CV and HEV). This data set consists of 130,305 records, each representing a SbS measurement of the following:

- Position of the vehicle (Latitude/Longitude)
- An integer (1-75) representing the test run number
- A binary integer representing the vehicle type, either the CV (1) or the HEV (2)
- The benzene (BZ) emission rate (µg/sec)

- The carbon monoxide (CO) emission rate (mg/sec)
- The carbon dioxide (CO_2) emission rate (mg/sec)
- The formaldehyde (HCHO) emission rate (µg/sec)
- The nitrogen monoxide (NO) emission rate (µg/sec)
- The nitrogen dioxide (NO_2) emission rate (µg/sec)
- The particle number (PN) emission rate (#/sec)
- The link ID needed to map the emissions data to the GIS
- The functional class of the roadway

CVs and HEVs will be the dominant vehicle propulsion systems for the foreseeable future, so quantitative understanding of their differential emissions at the link level is important but understudied. Although many states are implementing new policies aimed at increasing the market penetration of full electric vehicles (EVs) (VDPS, 2016), most of these policies are targeted at new vehicle sales. Penetration of EVs into the privately-owned passenger-vehicle fleet in the U.S will lag behind new vehicle sales, depending on the average age of the fleet. Some recent studies showing that owners are keeping their vehicles longer in the U.S. (LeBeau, 2015), means fleet penetration will lag farther behind new vehicle sales than originally anticipated. The most ambitious global forecasts predict new EV sales in the light-duty market making up about 70% of all new vehicle sales by 2050 (Rissman, 2017), but the International Energy Agency (IEA) only estimates that figure translating to a stock share of about 40% (IEA, 2016).

Researchers have established the relationship between instantaneous vehicle-specific power (VSP), or the road load that resists vehicle propulsion, and resulting tailpipe emissions from a vehicle overcoming the resisting load. This field of work was built on the original presentation of VSP and its relationship to tailpipe emissions measurements presented in a dissertation by Jiménez-Palacios (1999). A decade later, the concept was adopted by the EPA as one basis for the MOVES mobile source emissions model. Others have established the sensitivity of VSP and emissions to road grade and have validated sources of elevation and road-grade data, like Light Detection and Ranging data (LIDAR), for the purposes of including road grade in vehicle activity calculations (Zhang & Frey, 2006). MOVES still lacks the capability of modeling HEVs.

Models that best represent vehicle activity and account for various activity scenarios, such as lead vehicle activity, car-following constraints, collision avoidance, etc., have been established and incorporated into microsimulation models. Efforts to refine these models to improve aspects such as maximum accelerations of light-duty (Rakha et. al., 2004) or heavy-duty vehicles (Rakha et. al., 2001), driver anticipation in car-following (Kesting and Treiber, 2008), and inter-driver variability in car-following (Ossen et. al., 2006), have all been supported by the use of field data to identify anomalies not accounted for in the current modeling procedures. Further, no microsimulation capable of calibrated HEVs operation are known. HEVs will have different power/weight ratios and corresponding differences in acceleration and VSP.

Recent efforts have calibrated microsimulation models specifically for the purpose of emissions modeling, with emphasis on vehicle activity calibration parameters as opposed to prior use of traffic simulation metrics, like queue lengths and travel times. For instance, recent work on vehicle speeds and accelerations (Jie et. al., 2013) or acceleration near target speed (Talbot et. al., 2014) emphasize the relationship between vehicle activity and emissions. Jie et. al. (2013) used a technique to minimize the difference between the simulated and observed cumulative probability distributions of vehicle activity parameters to achieve the best-fit speed, acceleration, and deceleration models (Jie et. al., 2013). A similar method is used in this study.

Data Analysis Methodology

The SbS data was tagged to the road link the test vehicle was traversing to connect SbS emissions rates to the physical characteristics of the roadway. A shapefile of these data is included in the electronic project data transmittal. This connection allowed the emissions rates from each vehicle (CV or HEV) for the seven pollutants to be compared using the K-S test, by link.

The K-S test was used to assess the difference between the cumulative distribution functions (CDFs) of the CV and HEV emissions samples on each link. The K-S test is a nonparametric hypothesis test (Mathworks, 2015) with test statistic D*, the maximum absolute difference between the cumulative distributions:

$$D^* = \max_x\left(\left|\hat{F}_1(x) - \hat{F}_2(x)\right|\right)$$

The application of the K-S test resulted in a hypothesis test result, an asymptotic p-value, and the test statistic, D*. The test statistic was regressed against the full set of roadway link characteristics. The multiple linear regression was conducted in TransCAD, using its linear regression model estimation tool. The least squares estimation procedure produces coefficients for each independent variable of interest, along with goodness-of-fit measures. The goodness-of-fit measures computed by the regression procedure include an analysis of variance table, an R-squared measure that tests the overall explanatory power of the model, a standard error of the estimate and a test of the significance of each parameter (t-score). The t-score is the ratio of the parameter to its standard error. A ratio of about 2 or above is considered significant to 95% confidence. The multi-regression results therefore allowed the team to identify the specific roadway characteristics that contribute to emissions differences between the vehicle types.

To explore the relationship between emissions rates and the 9 intersection-control/turning-movement types at the beginning and end of each link, each of these control types was applied in a cross-classification model (Ortuzar and Willumsen, 2011). Each control type was cross-classified with the variables from the regression models with the highest t-scores. The average D* was calculated for each cross-classified category and this value was used to calculate a residual for each of the 80 links in the study. From the residual, an R-squared was calculated for each of the cross-classification models.

Results

Emissions Difference by Link

Cumulative distributions (CDs) of the CO, CO2, PN, BZ, NO, NO2, and HCHO emissions rate distributions for each vehicle type (CV and HEV) for all 80 links compared by link using the K-S test established differences between the two propulsion systems. The CDs for the HEV was generally behind the CDs for the CV, as expected due to its generally lower emissions profiles. Significant differences between the CV and HEV were noted along multi-link corridors with downgrades or flat grades with few traffic controls.

Emissions Differences and Link Characteristics

To further evaluate this hypothesis, a step-wise, reductive regression was conducted, with D* as the independent variable and the road link physical characteristics in as the dependent variables:

- Grade (%)
- Speed Limit (mph)
- One-Way Lane + Shoulder Width (ft.)
- Width of the Median (ft.)
- Lanes Each Way
- One-Way Capacity (vph)
- One-Way Daily Capacity (vpd)
- 2010 AADT (both ways) (vpd)
- 2010 AADT / Daily Capacity (both ways)
- Horizontal Curvature (degrees)

Variables were removed from the regression if their t-scores were lower than 2.0, corresponding to a confidence interval of approximately 95%. The only variables that remained in the final models for each of the 7 pollutants were speed limit, maximum grade, and degree of horizontal curvature. Correlation coefficients between the 3 final dependent variables are 0.05, 0.01, and -0.01, so their independence is well established. Results of the final regression models for each of the 7 pollutants, including each estimated coefficient (β), its associated t-score, and the adjusted R-squared of each model, are provided in Table 1.

Table 1. Results of Final Regression Models

	CO		CO_2		PN		BZ		NO		NO_2		HCHO	
	β	**t**	**β**	**t**	**β**	**t**	**β**	**β**	**t**	**β**	**t**	**β**	**t**	**β**
Speed Limit	na		-0.01	-5.97	-0.00	-3.85	-0.01	-6.40	-0.01	-6.18	-0.01	-5.88	-0.01	-6.30
Maximum Grade	-0.01	-2.84	-0.02	-4.75	-0.02	-4.68	-0.02	-4.84	-0.03	-5.21	-0.02	-4.68	-0.02	-4.61
Horizontal Curvature	-0.01	-2.15	-0.02	-3.64	-0.01	-3.65	-0.02	-3.74	-0.02	-4.02	-0.01	-3.63	-0.02	-3.61
Constant	0.50	36.1	0.90	16.1	0.56	13.0	0.89	16.0	0.87	16.4	0.76	15.4	0.88	16.2
Adjusted R-squared	0.13		0.49		0.40		0.51		0.52		0.48		0.49	

na – Speed limit was not found to be significant in the final regression model for CO

The negative signs on the coefficients of each dependent variable in Table 1 indicate that increasing the magnitude of these coefficients (higher speed limits, steeper grades, and sharper curves) contributes to decreased differences in emissions between the two vehicle types. This finding confirms that the greatest emissions differences occur when the CV and HEV vehicles are least challenged by the physical infrastructure. In other words, the challenges of traveling at higher speed, climbing a hill, or navigating a sharp curve cause the CV and HEV to have similar emissions patterns. Along the test route, 31% of the roadway length had a speed limit of 55 mph or above, 24% of the roadway length had an uphill grade of 5% or above, and 18% of the roadway length had a degree of horizontal curvature greater than 5, so these differences are significant to cumulative vehicle emissions in a typical driving environment.

Influence of Intersection Control

Each control type was cross-classified with the strongest variables from the regression models – speed limit and maximum grade. For the cross-classification, speed limit was divided into 2 categories (low and high) and maximum grade was divided into 4 (negative, flat, low positive, and high positive). The average D* was calculated for each cross-classified category and this value was used to calculate a residual for each of the 80 links in the study. From the residual, an R-squared was calculated for each of the cross-classification models and compared to the R-squared for the regression models, as shown in Table 2.

Table 2. R-squared values for the cross-classification models and regression models

Emission Type	Cross-Classification Models Speed Limit x Control Type	Cross-Classification Models Max Grade x Control Type	Multi-Regression Models (Table 1) Speed Limit, Max Grade, and Horizontal Curvature Regression
CO	0.25	0.36	0.13
CO_2	0.44	0.62	0.49
PN	0.37	0.57	0.40
BZ	0.46	0.66	0.51
NO	0.44	0.64	0.52
NO_2	0.44	0.65	0.48
HCHO	0.45	0.65	0.49

These calculations are provided in the electronic project data transmittal. Overall, the cross-classified model with maximum grade and control type performed best, based on R-squared values from 0.36 to 0.66. The results in Table 2 indicate that the combination of intersection controls and turning movements at each end of the link is significant in determining emissions differences between the two vehicle types. Control types 1, 2, and 6 led to the highest values of D*, indicating differences in emissions between the CV and HEV vehicle types where links have:

1. Stop-Sign/Turn to Stop-Sign/Turn
2. Thru-Signal to Stop-Sign/Turn
6. Thru-Signal to Thru-Signal

This finding indicates that the effect of traffic controls must also be considered when modeling the effect of roadway infrastructure on SbS emissions from CVs vs. HEVs.

Conclusions

The objective of this research was to improve understanding of the differences in tailpipe emissions from the variable use of an internal-combustion engine—full-time use in the CV and part-time use in the HEV—and to relate these differences to physical characteristics of the roadway. A step-wise, reductive regression (conducted with the K-S test statistic as the independent variable and the physical characteristics as the dependent variables) showed that emission rates differences could be adequately modeled based on link speed limit, maximum grade, and degree of horizontal curvature. Increasing the magnitude of these variables (higher speed limits, steeper grades, and sharper curves) contributed to decreased differences in emissions between the CV and HEV, showing that times when the HEV's ICE was off resulted in the greatest differences between vehicles. Conversely, the challenges of traveling at higher speed, climbing a hill, or navigating a sharp curve caused the vehicles to behave more similarly in terms of emissions, likely because the HEV's ICE is constantly on under higher VSP operating conditions.

To explore the relationship between emissions rates and 9 intersection-control/turning-movement link classifications, each control type was cross-classified with the most significant regression model variables (speed limit and maximum grade) in a cross-classification model. The cross-classified model of maximum grade and control type performed best, indicating the importance of including the combination of intersection controls and turning movements at each end of the link on emissions differences between CV and HEV. For future applications to a more electrified vehicle fleet, the effect of traffic controls must be considered when modeling the effect of roadway infrastructure on SbS emissions.

The performance differences identified in this project confirm that engine-switching controls that are responsive to roadway characteristics are necessary. It should also be recognized that the results have direct implications for fuel consumption by electrified vehicles due to the results obtained here for CO2 (CO2 and fuel consumption being closely related via mass balance). However, future research is needed to refine the mapping of roadway characteristics to emissions rates under a variety of engine control strategies for HEVs. It is not clear what control strategies for an HEV would reduce emissions the most as these roadway characteristics are encountered. Additional research can seek to modify the control strategies between a strategy that is optimized for performance (without regard to roadway characteristics), a strategy that is optimized for fuel economy (without regard to roadway characteristics), and a strategy that is optimized to minimize emissions by responding to the oncoming roadway characteristics. This type of evaluation will provide definitive evidence of the need for responsiveness to the roadway characteristics, as well as providing an initial understanding of specific engine-control strategy needed to control the propulsion of a HEV to reduce emissions and fuel consumption.

Limitations

A key explanatory variable that is missing from this analysis is the traffic conditions when the test runs were conducted. HEVs perform differently than CVs in various traffic conditions, and this can't really be tied to infrastructure, but including roadway congestion in a similar future analysis would resolve this gap. Real-time indicators of traffic congestion may be equally important for engine-control strategies as the physical characteristics of the roadway. Improving the engine-control aspect of HEV operation will require these types of real-time information in the on-board energy strategy.

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Data Management

Products of Research

This project leveraged prior UTC-funded work that developed methods and unique databases of second-by-second (SbS) on-board vehicle emissions data for estimating emissions differences between conventional vehicles and hybrid-electric vehicles. The team used SbS emissions data obtained from a series of 75 test runs driven by a single driver over 18 months in 2010 and 2011, across all seasons and at a variety of hours in the day. The suites of emissions data collected during the test runs were isolated by the road segment the vehicle was traversing at the time. Spatial processes were used to associate the emissions data with the characteristics of the roadway on which the vehicle was operating at the time, by assigning each emissions data point a Road Segment ID. For each road segment in the project, then, the following data is available:

ID	TransCAD native feature ID
Dir	Link direction: 0 - two-way; 1, -1 - one-way
Length	Link length (miles)
SP2 Link ID	Link ID corresponding to this study data
LINK_NAME	Name of roadway represented by the link
Daily_Cap	Daily roadway capacity (vehicles per day)
Hourly_Cap	Hourly roadway capacity (vehicles per hour)
SPEED_LIMIT	Speed limit (mph)
AADT	Annualized Average Daily Traffic for 2010 (from traffic counts)
AADT/Daily_Cap	AADT / Daily roadway capacity
GRADE_min	Minimum grade (%) on the roadway represented by the link
GRADE_max	Maximum grade (%) on the roadway represented by the link
GRADE_avg	Average grade (%) on the roadway represented by the link
HC Degree	Horizontal curvature (degrees)
Lane Width	Lane width (ft)
Shoulder Width	Right shoulder width (ft)
Lane + Shoulder	Width of the travelled way (lane + shoulder)
Median Width	Width of the roadway median (null if none)
Lanes Each Way	Number of lanes of travel in each direction
Control_Type	Intersection- control / turning-movement type at each end of the link (1 thru 9)
Speed_Limit_Cat	Speed limit category (low/high) for cross-classification analysis
L+S_Cat	Maximum grade category (negative, flat, low positive, and high positive) for cross-classification analysis

The distributions of specific SbS emissions data were compared using the K-S test, resulting in a D* statistics for each link in the study. These data were regressed against the physical characteristics above.

Data Format and Content

These datasets are in a fixed-format binary file (.bin) or a database file (.dbf) that is associated with a shapefile. Metadata for the fields in the shapefile are contained in a MS Excel file called "Links Metadata." The D* statistics and the results of the cross-classification modeling are contained in a MS Excel file called "Cross-Classification Analysis."

Data Access and Sharing

Sullivan, James; Sentoff, Karen (2019), Identifying Roadway Physical Characteristics that Contribute to Emissions Differences between Hybrid and Conventional Vehicles, DataONE Dash, Dataset, https://doi.org/10.15146/R36975

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