TECHBRIEF

Perspectives on Fuel Consumption and Air Contaminant Emission Rates by Highway Vehicles

FHWA Contacts: Howard A. Jongedyk, HRDI, (202) 493-3077
Michael Savonis, HEPN, (202) 366-2080

Volpe National Transportation Systems Center: Gregg Fleming, DTS-34, (617) 494-2372

The Federal Highway Administration—in collaboration with the Transportation Research Board, the National Cooperative Highway Research Program, State departments of transportation, and other Federal agencies—has been investigating the effects of highway transportation on air quality. These investigations have primarily dealt with the evaluation of air-contaminant emissions produced by motor vehicles at various speeds and under various highway conditions. Dispersion of air-contaminant emissions in various areas has been analyzed.

Highway agencies are also mandated to evaluate whether mobile-source emissions conform to State implementation plans and to make adjustments, as required, to meet ambient air quality standards.

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

www.tfhrc.gov

Highway traffic operations, pavement conditions, and highway designs affect rates of fuel consumption and air contaminant exhaust emissions, as well as the types and numbers of highway vehicles and the mileage driven by these vehicles. However, the fuel consumption and emissions produced are not dependent only on the vehicle mix and miles traveled.

This TechBrief summarizes the investigation, "Highway Effects on Vehicle Performance," undertaken at the Volpe National Transportation Systems Center. It refers to numerous other related efforts. The report, *Highway Effects on Vehicle Performance,* Publication No. FHWA-RD-00-164, has been placed on the Federal Highway Administration (FHWA) website (*www.tfhrc.gov/hnr20/00164.htm*).

The main product of this study is a model, "Highway Effects on Vehicle Performance" (HPP), a computer program that calculates estimated fuel consumption and exhaust emission rates and the amounts of each for a given highway segment for one or more vehicles (traffic) as determined by the user for highway geometric factors and idling or speeds, and accelerations (external loads, also gears) and presents the results, including cumulative results, in both pictorial and numerical forms. Hence, one can implement the model to estimate the effects of highway geometry and pavement and/or traffic conditions. Essentially, the model combines external loads from all sources, namely rolling resistance, aerodynamic drag, accelerations (inertia), grades, curves, and vehicle idling with essentially engine/vehicle maps that provide the rates of fuel consumption and air contaminant emissions for the condi-

tions of the external loads and engine speeds and gears or vehicle idling, as appropriate. (Internal energy losses for the vehicle could be considered.) For most evaluations, a given warmed-up vehicle is said to have external or road loads for various speeds and accelerations on a straight, flat, smooth highway with no ambient wind.

A CD-Rom has been prepared that contains the following:

- *Highway Effects on Vehicle Performance*, Publication No. FHWA-RD-00-164.
- The program, "Highway Effects on Vehicle Performance (HPP)," developed by Klaubert, West, and Crowley. (Questions may be addressed to Douglas Crowley, (202) 493-3214, or M. West, (617) 494-3417). Copies of the CD-Rom have been given limited distribution. Requests for copies should be addressed to the National Technical Information Service (NTIS), Springfield, VA 22161.

The investigation, "Highway Effects on Vehicle Performance," included:

- Instrumenting four vehicles to measure and record propulsive demands, while operating on highways with appropriate geometric features, such as grades and curves.
- Determining road loads for three vehicles.
- Measuring three test vehicles' fuel consumption rates on a programmable large-roll chassis dynamometer versus speed, load, and transmission gears and then developing databases for the three vehicles, relating fuel consumption rates to road loads at all speeds and loads (for one of the three vehicles, exhaust emission rates were also included).
- Testing the variability of driver performance for one of the instrumented vehicles in order to determine the significance of driver variability on estimates of fuel consumption and exhaust emissions for a given speed or set of conditions.
- Developing a single equation relating torque increase on a curve to lateral acceleration relative to a straight road for general application to all automotive vehicles.
- Developing a method for comparing the rolling resistance of pavement surfaces using a vehicle of known mass and aerodynamic drag on pavement of a known grade and curves using a vehicle instrumented for measurements of drive-shaft torque and speed for small time intervals or distances such as 5 m.
- Demonstrating for one vehicle that the energy loss in the drive axle and tires was described as a loss in torque or tractive force expressed as a quadratic function of only total drive torque of tractive force, independent of speed as an operative variable.
- Demonstrating a technique using drive-shaft torque on an instrumented vehicle to very consistently determine vehicle road load as a quadratic function of speed.

For the study, "Highway Effects on Vehicle Performance," there were only four vehicles tested. However, for these vehicles, load measurements were made with a large-roll dynamometer and by drive-shaft torque measurements to provide measurements on the road. This study is only one of numerous efforts to evaluate the fuel consumption and exhaust emission rates of carbon monoxide, nitrogen oxides, and hydrocarbons. In the event that the measurements were made from the foregoing emission rates and carbon dioxide emission rates, the fuel consumption rates could be calculated by carbon balancing and then converting the weights of the carbon into gasoline weights and volume of gasoline (gallons).

The references listed below also include discussions of vehicle external loads and other factors affecting fuel consumption and air contaminant emission rates, testing of vehicles for external loads versus emission and fuel use rates and the use of modal models. Modal models for one or more vehicles give fuel consumption and/or air contaminant emission rates that are dependent on high-

way and pavement conditions and modes of operation of vehicles, such as idling, acceleration, cruising at a constant speed, and deceleration, and vehicle characteristics, such as engine maps. An example of modal models include the HPP model in the study, "Highway Effects on Vehicle Performance," and modifications for traffic models. There are also numerous effects of highway pavement surfaces and other factors on rolling resistance, driver performance, and aerodynamic drag (which includes the effects of air density and direction velocities and the wind gusts (for example, colder air has a higher specific weight and, thus, more drag due to the higher density of cold air).

The modal models are superior to the MOBILE models. MOBILE models have been developed and mandated by the Environmental Protection Agency (EPA) to generate air contaminant emission rates versus speeds based on sample test data and an area's vehicle road network and vehicle fleet, and whether an area has put certain policies in place, such as required inspection and maintenance. Based on precisely defined emission rates for various speeds and vehicle-miles traveled in that area, the gross air contaminant emission rates are estimated. MOBILE models neither do justice to areawide air pollution problems, except to make gross estimates since they do not adequately consider the fate of exhaust air contaminants, nor do they adequately address small project areas. The MOBILE models do not consider the grades or curves of highways or the effects of pavement conditions. Nonetheless, they have been mandated by regulations as tools in evaluations as to whether highway emissions conform to an area's quotas for motor vehicle emissions given in a State Implementation Plan (SIP). MOBILE model usage puts a heavy emphasis on an area's vehicle mix and miles traveled. They offer no significant assistance in evaluations of the effects of pavements, highway design features such as grades and curves, or changes in traffic flow (amount of idling and acceleration as opposed to more constant speeds). Several reference listed (for example, see Russell) discuss the merits of modal models in contrast to the mandated MOBILE models (EMFAC models are California versions of MOBILE models.)

Simulation models, as defined more completely in the references, have been developed to estimate vehicle performance or fuel consumption and/or air contaminant emission rates based on external loads and relevant engine and vehicle component parts and their responses or "maps" for existing untested or as yet unbuilt conceivable vehicles.

VEHSIM was one of the first simulation models. (Contact H. Gould, Volpe National Transportation Systems Center, Cambridge, MA, (617) 494-2134.) It is referred to in Publication No. FHWA-RD-00-164 as offering a means of synthesizing data for the HPP model for unmeasured vehicles. VEHSIM and numerous subsequent models have been calibrated using appropriate validation tests (measurements of fuel consumption or emission rates versus model estimates) for sample vehicles.

Since 1995, the leading simulation model developed, validated, and widely used is ADVISOR, which was developed by the National Renewable Energy Laboratory of Golden, Colorado (Wipke). It is used by more than 2,000 users worldwide. It has the capability to model conventional, hybrid, or electrical vehicles for fuel consumption and air contaminant emission rates. It has been checked for fuel consumption and air contaminant emission rates for selected vehicles. This model not only can make estimations of current vehicles that may not have had actual measurements, but also can be used to make estimations of unbuilt vehicles being conceived and designed (*www.ctts.nrel.gov/analysis/advisor_doc/advisor_ch1.htm*).

Present Action

Use modal models with the available data on fuel consumption and air contaminant emission rates related to external loads for one or more vehicles where the external loads can be evaluated from road conditions, aerodynamic drag, grade, curves, speeds, and accelerations. Such data can be obtained from measurements on the vehicles or similar vehicles. Use a simulation model such as ADVISOR to make estimations of vehicle performances where there are no data or when projections for future vehicles are desired (vehicle mix estimations to represent traffic).

Future Prospects

With the expected improvements in vehicle performance with regard to fuel consumption and air contaminant emission rates, it is expected that the impacts of highway vehicles on fuel consumption and air pollution will gradually be reduced, assuming no significant changes in vehicle operations or increases in vehicle-miles traveled.

Several sources of such improvement include:

- Improved tires to provide lower rolling resistance.
- Reduction of energy losses during braking by using electrical systems for regenerative braking.
- Reduced internal combustion engine operations during idling.
- Pre-warmed vehicles to reduce cold-start emissions from engines and to make the catalytic converter more useful and improve the fuel economy using storage of energy at least for a time of 2 to 3 days (high-temperature energy or increased electric energy battery storage).
- There can also be improvements in fuel consumption and air contaminant emission rates by better pavement design and management, bare (snow-free/ice-free) pavements, and dry pavements, and improved highway design by optimizing grades and curves and wind exposures, and decreasing irregular speeds, accelerations, and decelerations as opposed to more constant speeds by traffic or highway management (Intelligent Transportation Systems).

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Researcher—This TechBrief is based mainly on a study performed at the Volpe National Transportation Systems Center by E. Klaubert, *Highway Effects on Vehicle Performance*, which is available at *www.tfhrc.gov/hnr20/00164.htm*. Numerous other studies mentioned in the references provide additional information and concepts supplementing the study by Klaubert.

Distribution—This TechBrief is being distributed according to a standard distribution. Direct distribution is being made to the Resource Centers and Divisions.

Availability—The primary report, Highway Effects on Vehicle Performance (Report No. FHWA-RD-00-164), is available at *www.tfhrc.gov/hnr20/00164.htm.* Other references are available from the organizations or agencies cited.

Key Words—Air pollution emissions, vehicle external loads, fuel consumption rates, road load tests, driver variability, lateral acceleration, aerodynamic drag, vehicle rolling resistance, chassis dynamometer, drive shaft torques, vehicle/highway performance predictor algorithm, simulation models, VEHSIM, ADVISOR.