FHWA Research and Technology Evaluation

# Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs

Final Report
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U.S. Department of Transportation
**Federal Highway Administration**

## Foreword

The Federal Highway Administration's (FHWA's) Research and Technology (R&T) Evaluation Program seeks to assess and communicate the benefits of FHWA's R&T efforts, ensure that the organization is expending public resources efficiently and effectively, and build evidence to shape and improve policymaking. FHWA partners with State transportation departments, local agencies, industries, and academia to conduct research on issues of national significance and accelerate adoption and deployment of promising research products.

This report examines how FHWA's investment in updating vehicle operating cost (VOC) models affected early interest, application, and response to the new VOC models. The findings of this report should be of interest to engineers, economists, practitioners, researchers, and decisionmakers involved with the estimation of VOCs, fuel consumption, and highway performance.

Jonathan B. Walker
Acting Director, Office of Corporate Research, Technology, and Innovation Management

## Notice



## Quality Assurance Statement



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| SI* (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | **NOTE**: volumes greater than 1,000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2,000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2,000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/m2 | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 2.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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# List of Abbreviations

| Abbreviation | Definition |
|---|---|
| ASCE | American Society of Civil Engineers |
| ASU | Arizona State University |
| COR | Contracting Officer's Representative |
| C&P Report | Conditions and Performance Report |
| EPA | Environmental Protection Agency |
| FHWA | Federal Highway Administration |
| HERS | Highway Economic Requirements System |
| ISAP | International Society of Asphalt Pavers |
| ITS | Institute of Transportation Studies |
| LCA | lifecycle assessment |
| MOE | measures of effectiveness |
| MOVES | Motor Vehicle Emission Simulator |
| NDS | naturalistic driving study |
| RID | Roadway Information Database |
| RILEM | Réunion Internationale des Laboratoires et Experts des Matériaux |
| R&T | Research and Technology |
| SHRP 2 | second Strategy Highway Research Program |
| TC-PFE | Technical Committee: Pavement Field Evaluation |
| TRB | Transportation Research Board |
| TRDF | Texas Research and Development Foundation |
| USDOT | U.S. Department of Transportation |
| VOC | vehicle operating cost |

# Executive Summary

## Purpose of the Evaluation

This document presents an evaluation of the Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs (VOCs) research project conducted by a research contractor for the Federal Highway Administration (FHWA). This document focuses on short-term outcomes of the VOC research and lessons learned during the project that could benefit similar projects in the future.

## Project Background

In September 2014, the FHWA Office of Transportation Policy Studies engaged a research contractor to update existing VOC models. FHWA uses these VOC models in the Highway Economic Requirements System (HERS) model for benefit-cost analysis to rank and select potential highway improvement projects. The existing VOC models are based on the Zaniewski equations developed in 1982.(2) Multiple patches were added to the VOC equations over the years to adapt them to evolving technologies, but by 2014 a model update was clearly needed. The 5-yr research project conducted by the research contractor would update and enhance the VOC estimation methodology. It would provide estimates for an updated vehicle fleet and create models that could be adapted to new technologies while also accounting for new parameters (e.g., roadway characteristics, pavement roughness) not previously included in HERS.

## Methodology

The original evaluation plan focused on longer term or indirect impacts of the updated VOC models, including how the research contractor's work changed the quality and usability of FHWA models and influenced policymaking. However, schedule changes within the contract performance period and the separate implementation period impacted the delivery date of the models, reducing the time available for industry stakeholders and the larger community to adopt the models. As a result, the evaluation team was not able to fully assess the impacts of the VOC models. The evaluation team, therefore, revised the evaluation plan to focus on short-term outcomes of the Enhanced Prediction of Vehicle Fuel Economy and Other VOC research project.

The evaluation team assessed two outcomes:

- Early interest and application of the updated VOC models.
- Internal response to, and perception of, the updated VOC models.

The evaluation team developed evaluation hypotheses and measures of effectiveness (MOE) for each outcome. The MOE were assessed using information from reports and other deliverables developed by the research contractor, along with interviews with U.S. Department of Transportation staff and contractors (i.e., internal stakeholders). The team also used the interviews with internal stakeholders to identify lessons learned, along with recommendations for avoiding similar issues in future research efforts.

# Findings

The evaluation findings are summarized as follows.

### Evaluation Area 1: Early Interest and Application of the Updated VOC Models.

- Finding 1a: The outreach activities conducted by the research contractor during the course of the research and after the delivery of the updated VOC models introduced the procedures and models to hundreds of public and private entities.

- Finding 1b: Interested parties from academia, as well as the public and private sectors, reached out to FHWA and sometimes to the research contractor directly for more information on the models, including a private company that planned to incorporate the methodology into its pavement lifecycle assessment software.

Overall, the early interest and planned use of the models support the hypothesis that the updated VOC models will generate interest and usage by government and nongovernment entities that see value in VOC equations with updated fuel and nonfuel cost estimates.

### Evaluation Area 2: Internal Response to, and Perception of, the Updated VOC Models.

- Finding 2a: Stakeholders interviewed for the evaluation described the updated VOC models as an improvement over current methods, because the updates brought the VOC models into alignment with the current vehicle fleet and advanced drivetrain technologies. The models were described as incredibly detailed, with the potential to improve VOC estimates in HERS and other government efforts, such as the Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) model.(3)

- Finding 2b: Despite the potential of the updated VOC models, stakeholders who reviewed specific VOC models voiced some concerns with specific equations and their outputs. Review of the fuel economy models identified abnormal fuel economy estimates (at steep grades). Stakeholders raised other concerns regarding the outputs and complexity of the vehicle depreciation model. Since the conclusion of the evaluation study period, work has continued on these equations, and they have been revised to account for these issues.

Taken together, the feedback provided by internal stakeholders does not fully support the hypothesis that they will have a positive response to the updated VOC models based on perceived increases in quality and usefulness. While the updated VOC models have the potential to improve VOC estimation, further testing and review are needed before the quality and usefulness of model outputs can be fully assessed.

# Lessons Learned and Recommendations

In the long term, the updated VOC models may improve the state of the art in VOC estimation, but in the near term, specific aspects of the models need additional vetting. A common perspective emerging from the evaluation interviews was that the contractor's research could have been more closely aligned with the existing VOC models. Some alignment issues resulted from the research contractor's focus on developing models that could be adapted for a future vehicle fleet, which is expected to include more hybrid electric and alternative-fuel vehicles. While orienting the research toward the future was seen as a positive, those involved in the HERS implementation team review process questioned whether the research contractor should have focused more on developing the new VOC models for the purpose of updating HERS.

Based on feedback from internal stakeholders reviewing and testing the VOC models, conventional project oversight methods—such as gathering stakeholder feedback and reviewing progress reports, which are sufficient for many projects—may not have fostered sufficiently foresighted review of the research progress on the VOC models, given the model complexity. While the research contractor updated the VOC models within the specified contract period, the models did have issues with respect to fuel economy and vehicle depreciation assumptions. These issues may not have been fully anticipated during project oversight due to the model complexity, but future research should ultimately rectify these issues.

To ensure better understanding of research expectations and more foresighted review of research progress, the evaluation team recommends the following actions:

- FHWA and researchers should establish an early agreement on research assumptions, baselines, and expectations to ensure that research more fully reflects FHWA's priorities.
- FHWA and researchers should develop a theory of change (e.g., logic model) that maps out how research activities feed into outputs and affect future outcomes, if applicable.
- Contracts for complex research projects should include more engaged methods of project oversight and progress review. While conventional methods of progress report review and stakeholder forums would be sufficient for simpler projects, complex projects should regularly convene staff and stakeholders to proactively discuss potential concerns and explicitly approve research progress.
- Research reviewers should be involved with model development and testing at the earliest stage feasible for research projects that develop novel models or technologies.
- FHWA staff and other stakeholders, building off an earlier lesson learned, could periodically revisit project expectations and theory of change (e.g., logic model) to ensure that a given contract continues to proceed according to expectations or is modified to account for changes in expectations.

From an evaluation perspective, the VOC project illustrates key risks with conducting a prospective evaluation of future impacts. Although the research contractor delivered the VOC models to contract specification and within the contract performance period, schedule changes within that performance period limited the evaluation team's ability to assess uptake and impacts of the revised VOC models. Particularly for prospective evaluations, future evaluation teams should more carefully assess the likelihood and impacts of schedule risks and develop appropriate contingency plans before those risks occur.

# 1. Introduction

## 1.1 Evaluation Purpose

The Federal Highway Administration (FHWA) initiated the Research and Technology (R&T) Evaluation program to help FHWA leadership, along with program and project managers, communicate the impacts of their research, ensure resources are being expended efficiently, and build evidence to inform future projects and policymaking.

To further these goals, the R&T Evaluation program planned to evaluate the Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs (VOCs) research project conducted by a research contractor for FHWA. The evaluation team aimed to assess the short-term outcomes and longer term impacts of the updated VOC models. However, the evaluation plans were modified as a result of schedule changes within the VOC contract performance period (see appendix C for task deliverable dates) and the separate implementation period for these models. The schedule changes reduced the time available for industry stakeholders and the larger community to adopt the VOC models, thereby limiting the evaluation team's ability to assess the usage and impact of the updated VOC models. This document represents an evaluation focused on shorter term outcomes of the VOC research and lessons learned during the project that could benefit similar projects in the future.

## 1.2 Background

In September 2014, the FHWA Office of Transportation Policy Studies engaged a contractor to conduct research and analysis related to VOC estimation. VOC estimates and methodologies are used by FHWA's Office of Transportation Policy Studies as inputs into the Highway Economic Requirements System (HERS) model. The HERS model uses benefit-cost analysis to rank and select potential improvement projects and estimate the investment levels needed to attain various targets. The HERS model is also an important component of the biennial *Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance* Report to Congress (C&P Report).[(4)]

Before this project, the VOC equations used in HERS were based on equations developed by Zaniewski et al. in a 1982 study, known as the Texas Research and Development Foundation (TRDF) VOC models.[(2)] As technology and vehicle fleets developed and changed over time, the TRDF model became outdated. Multiple patches were added to the HERS equations over the years to adapt them to current technologies, but updated models were clearly needed. Until recently, TRDF model updates were considered cost-prohibitive, but due to technological innovations, such as the collection of onboard recorder data from vehicle manufacturers, an update became feasible. The FHWA contractor's research represents the first systematic attempt to update the VOC equations in nearly 40 yr.

The research contractor initiated an updated analysis of VOCs in September 2014 under the supervision of the FHWA Office of Transportation Policy Studies. The research included developing predictive models of vehicle fuel consumption and four nonfuel VOCs: oil consumption, tire wear, maintenance and repair, and vehicle depreciation. The contractor sought to create models that reflected the current vehicle fleet but could be adapted to new technologies. The models would also include parameters not previously included in the original HERS model (e.g., driving cycles, roadway characteristics, pavement roughness).

The first 2 yr of the project were to consist of engineering work related to updating existing equations from the TRDF model and enhancing the VOC estimation methodology (as shown in appendix C, table 5). The last 3 yr would be used for implementing the models and evaluating the outcomes of the research effort. However, schedule changes within the contract period led to the initial technical work taking approximately 4 yr, thus compressing the model integration and outcome monitoring work to approximately 1 yr. While these schedule changes did not affect the overall contract performance period, the evaluation team noted that these schedule changes shifted delivery of various research tasks and compressed the task focused on assessing the impacts of the new VOC models.[1]

The research contractor submitted the phase I report that included physics-based models of vehicle fuel economy in May 2017.[2] The phase II report, submitted in December 2018, expanded the analysis to include models for the nonfuel VOCs.[3] An outreach summary report was delivered in July 2019.[4]

Due to the timing of the 24th C&P Report to Congress (transmitted to Congress in October 2021), the updated VOC models have not yet been incorporated into the HERS model, nor have the reports prepared for the Enhanced Prediction of Vehicle Fuel Economy and Other VOC research project been published.(4) The evaluation is, therefore, based on feedback from internal stakeholders and analysis of potential users who have been exposed to the updated VOC models through the research contractor's outreach activity.

[1]Volpe National Transportation Systems Center. 2016. *Final Task Plan (August 2016 Update) for Research and Technology Evaluation: Vehicle Operating Costs*, Washington, DC: FHWA (Unpublished).

[2]Hajj, E. Y., H. Xu, G. Bailey, M. Sime, R. Chkaiban, S. F. Kazemi, and P. E. Sebally. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs, Phase I: Modeling the Relationship Between Vehicle Speed and Fuel Consumption*. Washington, DC: FHWA (Unpublished).

[3]Hajj, E. Y., M. Sime, R. Chkaiban, G. Bailey, H. Xu, and P. E. Sebally. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs, Phase II: Modeling the Relationship Between Pavement Roughness, Speed, Roadway Characteristics and Vehicle Operating Costs*. Washington, DC: FHWA (Unpublished).

[4]Hajj, E. and R. Chkaiban. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs. Evaluation of the Use of Procedures Developed*. Washington, DC: FHWA (Unpublished).

# 2. Updated Evaluation Design

The original evaluation plan included an assessment of both the short-term outcomes and longer term impacts of the updated VOC models. Assessing the short-term outcomes would include identifying entities interested in using the equations, understanding how they planned to use the equations, and capturing their perceptions of the updated VOC models in terms of quality and usefulness. The longer term impacts were intended to measure how the research contractor's work changed the quality and usability of FHWA models and affected the operations of the entities using the updated VOC models. Due to a longer time frame, 3–5 yr, necessary for the longer term impacts to reveal themselves, this evaluation will focus only on the short-term outcomes and will not assess any long-term impacts of the models.

## 2.1 Short-term Outcomes

The two outcomes addressed in the evaluation are shown in table 1, along with their evaluation hypotheses, measures of effectiveness (MOE), and information sources. The methodology for assessing these outcomes is described in section 2.2.

**Table 1. Evaluation areas and assessment criteria.**

| Short-Term Outcomes | Evaluation Hypothesis | MOE | Information Sources |
|---|---|---|---|
| Early interest and application of updated VOC models | Updated VOC models will generate interest and usage by government and nongovernment entities that see value in the updated fuel and nonfuel VOC equations. | 1. Number and quality of research contractor outreach activities.<br>2. Identification of entities interested in updated VOC models, i.e.:<br>• Attended trainings or webinars.<br>• Contacted the contractor directly for information.<br>3. Summary of information sought and description of potential use. | • Research contractor outreach activity tracker.<br>• Research contractor outreach summary report.<br>• Interview with research contractor.<br>• Interview with contacts. |
| Internal response to, and perception of, the updated VOC models | Internal stakeholders will have a positive response to the updated VOC models based on perceived increases in the information's quality and usefulness. | Attitudinal responses to interview questions. | Interviews with FHWA and USDOT staff reviewing the models and contractors implementing the models. |

USDOT = U.S. Department of Transportation.

The first outcome—early interest and application of updated VOC models—assesses the success of early outreach activities aimed at educating potential users on the updated VOC models, thereby generating interest and potential use. The second outcome—internal response to, and perceptions of, the updated VOC models—assesses the perceptions of stakeholders from FHWA, U.S. Department of Transportation (USDOT) staff reviewing the models, and contractors implementing the models. The evaluation also includes a set of lessons learned and related recommendations that could benefit similar projects in the future.

## 2.2 Evaluation Methodology

Evaluation hypotheses and MOE were developed for each outcome area. The MOE were analyzed using information from reports and materials provided by the research contractor and interviews with FHWA and its contractors.

### Short-term Outcome: Early Interest and Application of the Updated VOC Models

As part of its contract with FHWA, the research contractor summarized and submitted information relating to the usage and application of the updated VOC equations. Outreach activity from May 2017 through October 2020 was cataloged and summarized through the FHWA VOC Models Outreach Activities Tracker.[1] The research contractor summarized information regarding interest in, and application of, the models in an outreach report, *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs Evaluation of the Use of Procedures Developed*.[2] The evaluation team reviewed the research contractor's report and synthesized the activity data to assess short-term outcomes.

> Hypothesis 1: The updated VOC models will generate interest and usage by government and nongovernment entities that see value in VOC equations with updated fuel and nonfuel cost estimates.

The MOE that will inform this hypothesis include the following:

- Number and type of outreach activities conducted by the research contractor.
- Identification of entities interested in the updated VOC models.
- Summary of information sought and description of potential use.

The data sources used for this assessment are the activity tracker, outreach report, research contractor interview, and contact interviews.

### Short-term Outcome: Internal Response to, and Perceptions of, the Updated VOC Models

This short-term outcome assessment summarizes how the updated VOC models were initially perceived by FHWA staff and its contractors who reviewed them or were involved in integrating them with HERS.

[1]Federal Highway Administration. 2020. VOC Models Outreach Activities Tracker (Unpublished).

[2]Hajj, E. and R. Chkaiban. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs. Evaluation of the Use of Procedures Developed*. Washington, DC: FHWA (Unpublished).

Hypothesis 2: Internal stakeholders will have a positive response to the updated VOC models based on perceived increases in quality and usefulness of the information.

The MOE that will inform this hypothesis are generally attitudinal responses to interview questions regarding the usefulness of the updated VOC equations.

The data sources used for this assessment are interviews with FHWA staff and contractors.

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# 3. Evaluation Findings

## 3.1 Early Interest and Application of the Updated VOC Models

Hypothesis 1: The updated VOC models will generate interest and usage by government and nongovernment entities that see value in VOC equations with updated fuel and nonfuel cost estimates.

The research contractor provided the information used to evaluate hypothesis 1 as part of the contract with FHWA through the outreach summary report and VOC Models Outreach Activities Tracker.[1,2] Early outreach activities included presentations based on the first phase of the research project. The presentations included updated driving cycles and fuel consumption research results. Later outreach activities included results from the second phase, which incorporated the effects of road curvature and pavement conditions into the fuel economy and nonfuel VOC equations. The focus of the two phases are described as follows:

- Phase I of the research contractor's VOC research focused on developing representative vehicle models and then simulating their operation using driving cycles (i.e., vehicle speed-time profiles) and respective highway grades (upslope/downslope) to predict the fuel economy for different driving scenarios (full, partial, or no access control).[3]

- Phase II focused on modeling the effects of road curvatures and pavement roughness on vehicle fuel consumption, as well as the effects of infrastructure physical and operating characteristics on nonfuel VOCs (i.e., tire wear, oil consumption, mileage-related vehicle depreciation, and repair and maintenance).[4]

Finding 1a: The outreach activities conducted by the research contractor during the course of the research and after the delivery of the updated VOC models introduced the procedures and models to hundreds of public and private entities.

The research contractor delivered an outreach summary report and an Excel® workbook documenting the outreach activities conducted during the contract period (VOC Models Outreach Activities Tracker). From May 2017 through September 2019, the research contractor presented findings to subject-matter experts at FHWA, held web meetings with industry stakeholders, and presented research findings at Transportation Research Board (TRB) events, academic conferences,

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[1]Hajj, E. and R. Chkaiban. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs. Evaluation of the Use of Procedures Developed*. Washington, DC: FHWA (Unpublished).

[2]Federal Highway Administration 2020. VOC Models Outreach Activities Tracker (Unpublished).

[3]Hajj, E. Y., H. Xu, G. Bailey, M. Sime, R. Chkaiban, S. F. Kazemi, and P. E. Sebally. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs, Phase I: Modeling the Relationship Between Vehicle Speed and Fuel Consumption*. Washington, DC: FHWA (Unpublished).

[4]Hajj, E. Y., M. Sime, R. Chkaiban, G. Bailey, H. Xu, and P. E. Sebally. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs, Phase II: Modeling the Relationship Between Pavement Roughness, Speed, Roadway Characteristics and Vehicle Operating Costs*. Washington, DC: FHWA (Unpublished).

and committees. Additional outreach activities and presentations occurred after the contract period and were recorded and sent to the evaluation team (October 2019 to October 2020). The total count of outreach activities pursued is summarized in table 2, and the full list of outreach activities can be found in appendix B.

**Table 2. Outreach activities.**

| Audience | Number of Activities |
|---|---|
| FHWA project results sharing meetings | 4 |
| TRB events | 6 |
| Government working group/committee presentations | 3 |
| Industry presentations/publications | 5 |
| Academic webinars/seminars | 2 |
| Private industry meetings | 3 |

In the outreach summary report, the research contractor described the results of particularly successful efforts to publicize the results of the VOC model development. Notably, the research contractor held discussions with a private building material manufacturing company regarding VOC procedures and model development, which concluded with the firm's decision to integrate certain VOC models into its lifecycle assessment (LCA) software. The research contractor additionally mentions participation in the TRB webinar, "Modeling the Relationship Between Vehicle Speed and Fuel Consumption," which was attended by stakeholders from 155 separate virtual sites, including 30 State departments of transportation.(5) The contractor also participated in a seminar at the University of California, Davis, on "New Relationship Models between Vehicle Speed Profile, Roadway Characteristics, Pavement Roughness, and Vehicle Operation Costs."(6)

Finding 1b: Interested parties from academia, as well as the public and private sectors, reached out to the research contractor directly for more information on the models, including a private company that planned to incorporate the methodology into its pavement LCA software.

In response to these outreach activities, FHWA and the research contractor received multiple requests for information from parties interested in learning more about the results of the VOC model development. The research contractor shared the phase I and phase II reports summarizing the results of the VOC model development with government and academic stakeholders, including researchers at the University of California Pavement Research Center and Arizona Department of Transportation, as well as with various interested parties from the private sector. In total, the research contractor responded to 12 direct requests for information through January 2020. Although it is not yet clear if these requests for information represent eventual use and application of the models, the requests do signal active interest across a diverse set of stakeholders. The expected incorporation of the updated VOC models into HERS, along with the formal publication of the research reports, should generate additional interest and use of the enhanced VOC models.

Overall, the early interest and planned use of the models support the hypothesis that the updated VOC models will generate interest and usage by government and nongovernment entities that see value in VOC equations with updated fuel and nonfuel cost estimates.

## 3.2 Internal Response to, and Perceptions of, the Updated VOC Models

Hypothesis 2: Internal stakeholders will have a positive response to the updated VOC models based on perceived increases in quality and usefulness of the information.

A range of views regarding the research effort and its outputs (see appendix A for list of interviewees) were obtained by interviews with FHWA staff, USDOT staff who reviewed the new VOC models and equations for implementation into HERS, and contractor staff involved with the VOC models and equations' implementation into HERS. This section summarizes the feedback received from these stakeholders. While several interviewees saw the research contractor's work as a worthwhile effort to update decades-old VOC research, others voiced concerns related to technical issues identified during the HERS implementation team review.

### Perceptions of the Updated VOC Models

Finding 2a: Stakeholders interviewed for the evaluation described the updated VOC models as an improvement over current methods, because the updates brought the VOC models into alignment with the current vehicle fleet and advanced drivetrain technologies. The models were described as having the potential to improve VOC estimates in HERS and possibly other government efforts, such as EPA's MOVES model.

Several internal stakeholders agreed that the Enhanced Prediction of Vehicle Fuel Economy and Other VOCs research project was a worthwhile effort to update the decades-old Zaniewski VOC equations.(2) One interviewee indicated that the updated driving cycles developed during the course of the research should result in improvements in the estimation of VOCs. Another described the research as follows:

> *"The research brings the VOC models up to modern standards by incorporating what has been learned in the past 40 years about how fuel economy varies as a result of different driving cycles and conditions."*[5]

This interviewee also credited the effort for bringing the VOC models into alignment with the current vehicle fleet and improved drivetrain technologies.

Other feedback indicated that the research provides a knowledge base that will allow VOC models to evolve as hybrid electric and alternative-fuel vehicles become a greater share of the national fleet. The research contractor included a range of vehicle powertrain configurations—such as hybrid electric, gas-ethanol (E85), and liquid natural gas—in the research to accommodate future technical advances in vehicle development.(5)

The VOC models developed by the research contractor were described as being very ambitious and incredibly detailed, providing fuel economy and nonfuel cost estimates for 30 separate vehicle models. The fuel economy model includes separate equations for each vehicle, often including a main equation, feeder equations (to calculate inputs to the main equation), and adjustments for

[5]External contractor (HERS Integration Review), phone interview conducted by evaluation team member Lora Chajka-Cadin in June 2021.

aspects such as curvature and pavement condition. In total, the fuel and nonfuel VOC models include nearly 2,000 equations:

> *"The VOC models are so detailed they can probably predict fuel economy down to the liter, although that level of detail is not necessary for planning models such as HERS."*[6]

This interviewee also noted that fuel economy measurements at this level may be useful as inputs to the EPA's MOVES model or to agencies or firms using microsimulation models to estimate the impacts of different highway designs on vehicle fuel consumption.

## Implementation Review

Finding 2b: Despite the potential of the updated VOC models, stakeholders voiced concerns with some of the model components during the HERS implementation team review. They had concerns regarding abnormal fuel economy estimates (at steep grades) and issues related to the complexity of the vehicle depreciation model.

The process of integrating the updated VOC models into HERS was daunting, requiring coding and testing of nearly 2,000 equations. Although the updated VOC models were seen as a positive step forward, several issues were identified during the HERS implementation team review.

### *Fuel Economy*

After the updated VOC equations were coded, the HERS implementation team ran tests with existing HERS data and found that, in some cases, fuel economy estimates behaved abnormally at steep grades, impacting the fuel economy and tire wear models. The abnormalities required the team to test and reestimate some equations using the World Bank's fourth Highway Development and Management Model.[(7)] The HERS implementation team indicated that the research contractor was very supportive, even after the VOC contract had expired, as they worked through this issue.

### *Vehicle Depreciation Model*

During the HERS implementation team review process, several issues were identified with the research contractor's mileage-related depreciation model, which incorporates publicly available data for vehicle valuation (e.g., age, miles traveled), depreciation from road conditions (e.g., grade, curvature, roughness), and driving cycles. The review indicated that the research contractor took inadequate account of the underlying model used to produce the publicly available data, treating the fitted model outputs as raw data when developing depreciation equations. It also appeared to the reviewers that the researcher made a conceptual mistake, confusing the age of the vehicle with the vehicle model year of production/vintage. The reviewers noted that the misinterpreted data and conceptual errors necessitated difficult functional forms to manage the data and yielded some questionable estimates.

> *"[There was] discussion that there was not enough rigor put into the estimation of non-fuel economy costs. There was good information from the physics, but not enough data on the market economics that went into vehicle cost."*[7]

[6]Ibid.

[7]USDOT Volpe Center Subject Matter Expert (document review), phone interview conducted by evaluation team member Lora Chajka-Cadin in April 2021.

Taken together, the feedback provided by internal stakeholders does not fully support the hypothesis that internal stakeholders will have a positive response to the updated VOC models based on perceived increases in quality and usefulness. While the updated VOC models can potentially improve VOC estimation, further testing and review are needed before the quality and usefulness of model outputs can be fully assessed.

# 4. Lessons Learned and Recommendations

The short-term outcome assessment associated with the updated VOC models indicates that the research can potentially improve VOC estimation. However, schedule changes within the contract performance period and the separate implementation period of the VOC models limited adoption and use of the updated VOC models within FHWA and prevented the evaluation team from assessing longer term impacts during the evaluation period.

This section describes the lessons learned during the Enhanced Prediction of Vehicle Fuel Economy and Other VOCs research project and provides recommendations for project and evaluation planning so similar issues may be avoided in the future.

## 4.1 Establish Agreement on Expectations at the Start of Research

A common perspective emerging from the evaluation interviews was that the research conducted could have been more closely aligned with the existing HERS VOC models. Some of the alignment issues resulted from the research contractor's focus on developing models that could be adapted for a future vehicle fleet, which is expected to include more hybrid electric and alternative-fuel vehicles. While orienting the research toward the future was seen as a positive, those involved in the HERS implementation team review process questioned whether the research contractor strayed too far from the purpose of updating HERS.

The evaluation team recommended that the following actions be taken to ensure future VOC- or HERS-related research aligns with FHWA's needs:

- FHWA and researchers should incorporate into the project scope of work their research assumptions, baselines, and expectations to ensure that research more fully reflects FHWA's priorities.
- FHWA and researchers should develop a theory of change (e.g., logic model) that maps out how research activities feed into outputs and affect future outcomes, if applicable.

## 4.2 Ensure More Engaged Review and Approval of Research Progress

Based on feedback from internal stakeholders reviewing and testing the new VOC models, conventional methods of project oversight—such as gathering stakeholder feedback and reviewing progress reports, which are sufficient for many projects—may not have fostered sufficiently foresighted review of research progress on the VOC models. Although feedback was gathered at numerous FHWA forums, as well as other forums and presentations during project development and through monthly oversight meetings with the Contracting Officer's Representative (COR), detailed review of the models and outputs typically occurred through the research contractor's periodic check-in reports. Internal stakeholders indicated that this process, given the complexity of the VOC models, may not have sufficiently addressed issues and potential changes.

> *"[The research contractor] published check in reports, which were sent for review from [redacted]. [I] provided comments, suggested updates, and added questions. After the feedback was provided, [the research contractor] would publish the final report. Some issues were addressed and some suggested changes made, but not all. It was noted that it was too late to address some issues."*[1]
>
> *"The time and resource demands for doing oversight can be large; however, if this [vehicle depreciation model issue] is a common situation, the lesson is that it is a useful expense of time."*[2]

While reviewing progress reports is a good practice, for more complex, critical projects, FHWA could consider periodically convening relevant staff to discuss a contractor's research progress and determine whether the research is heading in the right direction. Although for the VOC project a USDOT subject-matter expert participated in the review of the monthly progress reports, reviewing these reports tends to be an individual activity for which it is expedient to approve progress. However, ensuring that other experts are periodically brought together to discuss proactively their thoughts and any potential concerns would be beneficial. While such group reviews can incur additional time and money to be spent on the project, a more engaged review process can save resources in the long term.

Although the research contractor did support the HERS implementation team after delivery of the VOC models and even after the contract had expired, a more engaged review would have been needed during model development to remedy the missing driving cycles or address fuel efficiency issues on steep grades.

To improve short- and longer term outcomes for similar research projects in the future, the evaluation team recommends the following actions:

- Contracts for complex research projects should include more engaged methods of project oversight and progress review. Whereas conventional methods of progress report review and stakeholder forums would be sufficient for simpler projects, complex projects should regularly convene staff and stakeholders to proactively discuss potential concerns and explicitly approve research progress.
- Research reviewers should be involved with model development and testing at the earliest stage feasible for research projects that develop novel models or technologies.
- FHWA staff and other stakeholders, building off an earlier lesson learned, could periodically revisit project expectations and theory of change (e.g., logic model) to ensure that a given contract continues to proceed according to expectations or is modified according to changes in expectations.

[1]USDOT Volpe Center Subject Matter Expert (document review), phone interview conducted by evaluation team member Lora Chajka-Cadin in April 2021.

[2]USDOT Volpe Center Staff (HERS implementation team review), phone interview conducted by evaluation team members Greg Bucci and Daniel Friedman in May 2020.

## 4.3 Assess Evaluation Risks Carefully for Prospective Evaluations

From an evaluation perspective, the VOC project illustrates key risks with conducting a prospective evaluation of future impacts. While the VOC models were delivered to contract specifications and within the contract performance period, schedule changes within the performance period and the separate implementation period of these models limited the evaluation team's ability to assess uptake and impacts of the revised VOC models. Particularly for prospective evaluations, future evaluation teams should more carefully assess the likelihood and impacts of schedule risks and develop appropriate contingency plans in advance of those risks occurring.

# Appendix A: Evaluation Interviews

Table 3 is a list of people interviewed regarding the research effort and its outputs for the Enhanced Prediction of Vehicle Fuel Economy and Other VOC research project.

**Table 3. Internal stakeholder interviews.**

| Organization | Role | Interview Date | Follow-up Date |
|---|---|---|---|
| FHWA | Project COR | January 2020 | — |
| USDOT- Volpe Center | HERS implementation team reviewer | May 2020 | March 2021 |
| USDOT- Volpe Center | HERS implementation team reviewer | May 2020 | March 2021 |
| USDOT- Volpe Center | Subject-matter expert (document review) | April 2021 | — |
| External contractor | HERS integration team member | June 2021 | — |

—No data.

# Appendix B: Research Contractor Outreach Summary

Table 4 is a summary of all research contractor outreach activities conducted as part of the Enhanced Prediction of Vehicle Fuel Economy and Other VOC research project.

**Table 4. Summary of research contractor outreach activities.**

| Audience/ Purpose | Activity | Description | Date | Type |
|---|---|---|---|---|
| FHWA | FHWA VOCs project phase I meeting, Washington, DC | *Phase I: Modeling the Relationship Between Vehicle Speed and Fuel*[1] | 05/09/17 | Presentation |
| FHWA | FHWA VOCs project phase II meeting, Washington, DC | *Phase II: Modeling the Relationship Between Pavement Roughness, Speed, Roadway Characteristics, and VOCs*[2] | 10/10/18 | Presentation |
| FHWA | Meeting with FHWA to launch web application | "Estimating VOCs Calculator: A Web-based Application" | 06/11/20 | Meeting |
| FHWA | VOCs web application | WRSC website, "Vehicle Operating Costs Calculator"(8) | 02/18/21 | Online VOC calculator |
| TRB | TRB webinar | "Modeling the Relationship Between Vehicle Speed and Fuel Consumption"(5) | 03/14/18 | Webinar |
| TRB | TRB 98th Annual Meeting, Washington, DC | "Effect of Road Level of Service on Compact Car Fuel Economy Powered with Different Engine Types"(9) | 01/14/19 | Presentation (poster session) |
| TRB | TRB Committee on Characteristics of Asphalt Paving Mixtures to Meet Structural Requirement (AFK50) Meeting, Washington, DC | "Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs" (FHWA DTFH61-14-C-00044). Models and the potential applicability of the developed models | 01/16/19 | Presentation (committee meeting) |
| TRB | 2020 TRB Annual Meeting, Washington, DC | "Impact of Pavement Roughness of Fuel Consumption for a Range of Vehicle Types" | 01/14/20 | Presentation (poster session) |
| TRB | 2020 TRB Annual Meeting, Washington, DC | "Road Load-Based Model for Vehicle Repair and Maintenance Cost Estimation" | 01/15/20 | Presentation (poster session) |

[1]Hajj, E. Y., H. Xu, G. Bailey, M. Sime, R. Chkaiban, S. F. Kazemi, and P. E. Sebally. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs, Phase I: Modeling the Relationship Between Vehicle Speed and Fuel Consumption*. Washington, DC: FHWA (Unpublished).

[2]Hajj, E. Y., M. Sime, R. Chkaiban, G. Bailey, H. Xu, and P. E. Sebally. n.d. *Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs, Phase II: Modeling the Relationship Between Pavement Roughness, Speed, Roadway Characteristics and Vehicle Operating Costs*. Washington, DC: FHWA (Unpublished).

| Audience/ Purpose | Activity | Description | Date | Type |
|---|---|---|---|---|
| TRB | 2020 TRB Annual Meeting, Washington, DC | "Asymmetric Logistic Model for Estimation of Mileage-Related Vehicle Depreciation Function of Roadway Characteristics" | 01/15/20 | Presentation (poster session) |
| Other government stakeholders | SHRP 2 Safety Data Oversight Committee, Washington, DC | "Driving Cycle Development for Prediction of Vehicle Operating Cost— Application of SHRP 2 NDS and RID Data" | 05/11/17 | Presentation |
| Other government stakeholders | 17th Meeting of the Sustainable Pavements Technical Working Group, Reno, NV | "Enhanced Prediction of Vehicle Fuel Economy and Other VOCs"(FHWA DTFH61-14-C-00044) | 05/08/19 | Presentation |
| Other government stakeholders | Sustainable Pavements Technical Working Group | "Estimating VOCs Calculator: A Web-based Application" | 06/04/20 | Presentation |
| Industry | ISAP TC-PFE, Washington, DC | "Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs" | 01/07/18 | Presentation |
| Industry | ISAP TC-PFE, Washington, DC | "5-min Update on the Status and Overall Findings of VOC Project for Phase I and Phase II" | 01/13/19 | Presentation |
| Industry | ASCE International Conference on Transportation & Development | "Influence of Traffic Congestion on Non-Fuel Vehicle Operating Costs of Small Light Duty Vehicles" | 05/01/20 | Presentation |
| Industry | RILEM International Symposium on Bituminous Materials | "Enhanced Models for Vehicle Fuel Consumption for Life Cycle Assessment of Pavements"(10) | 06/01/20 | Paper/ Presentation |
| Industry | Paper publication for LCA 2020 | *Pavement, Roadway, and Bridge Life Cycle Assessment 2020: Proceedings of the International Symposium on Pavement. Roadway, and Bridge Life Cycle Assessment 2020*(11) | 06/06/20 | Publication |
| Academia | ITS-University of California, Davis Institute of Transportation Studies Seminar Series | "New Relationship Models between Vehicle Speed Profile, Roadway Characteristics, Pavement Roughness, and Vehicle Operating Costs"(6) | 04/26/19 | Presentation (seminar) |
| Academia | ASU Fall 2020 Seminar Series | "Updated Vehicle Operating Cost Models Function of Roadway Characteristics for an Array of Vehicle Classes and Technologies" | 10/14/20 | Presentation (webinar) |

SHRP 2 = second Strategic Highway Research Program; ISAP = International Society of Asphalt Pavers; TC-PFE = Technical Committee: Pavement Field Evaluation; ASCE = American Society of Civil Engineers; RILEM = Réunion Internationale des Laboratoires et Experts des Matériaux; ITS = Institute of Transportation Studies; ASU = Arizona State University; NDS = naturalistic driving study; RID = Roadway Information Database.

# Appendix C: Task Summary

Table 5 contains a description of each task item specified in the Enhanced Prediction of Vehicle Fuel Economy and Other VOCs research project, as well as the initial and updated due dates for each task. The table excludes task items 6 and 11, which were scheduled meetings between the research contractor and FHWA.

**Table 5. Research contractor VOC task summary.**

| Task Number | Description | Initial Due Date (months postaward)[1] | Updated Due Date (months postaward)[2] |
|---|---|---|---|
| 1 | Driving cycle development: controlled access facility. | 7 | 18 |
| 2 | Driving cycle development: partial or no access facility. | 8 | 19 |
| 3 | Fuel consumption for controlled access facility. | 11 | 26 |
| 4 | Fuel consumption estimates for roadways with partial or no access. | 12 | 29 |
| 5 | Phase I interim report. | 13 | 31 |
| 7 | Effects of infrastructure physical and operating characteristics on nonfuel VOCs. | 13 | 44 |
| 8 | Effect of road curvature on fuel consumption. | 15 | 37 |
| 9 | Incremental fuel consumption due to pavement roughness. | 17 | 40 |
| 10 | Phase II report. | 21 | 46 |
| 12 | Evaluation of the use of the current HERS procedures. | 24 | 49 |
| 13 | Evaluation of the use of the procedures developed. | 36 (after completion of phase I and phase II) | 12 (after completion of phase I and phase II) |
| 14 | Recommend procedures to adapt the fuel consumption for use in other models. | 36 | 54 |

[1]Federal Highway Administration. 2015. *Statement of Work for Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs.* RFP 31-10-14022, Washington, DC: FHWA (Unpublished).

[2]University of Nevada Reno. 2018. *Monthly Progress Report, October 19, 2019–November 18, 2018.* Contract No. DTFH61-14-C-00044. Washington, DC: FHWA (Unpublished).

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