Peer Review for the PQA/Ricardo Report "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies"

EPA United States Environmental Protection Agency

Peer Review for the PQA/Ricardo Report "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies"

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

EPA United States Environmental Protection Agency

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

ANN ARBOR, MI 48105

January 16, 2008

OFFICE OF
AIR AND RADIATION

MEMORANDUM

SUBJECT: Peer Review for PQA/Ricardo Report on "A STUDY OF POTENTIAL EFFECTIVENESS OF CARBON DIOXIDE REDUCING VEHICLE TECHNOLOGIES"

FROM: Cheryl Caffrey, Assessment and Standards Division
Office of Transportation and Air Quality, U.S. Environmental Protection Agency

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In July 2007, US EPA contracted with Perrin Quarles Associates, Inc. who subcontracted with Ricardo, Inc. to perform vehicle simulation modeling to estimate the impact of various technology packages on carbon dioxide emissions. The resulting report from Ricardo provides a detailed assessment of the carbon dioxide emissions reduction potential of a large number of conventional vehicle technology packages involving engine and transmission technologies as well as improvements in aerodynamics, tires, and accessories. The PQA-Ricardo report is entitled "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies".

Prior to the release of the Final Report from Ricardo, Inc., EPA provided a draft copy of the report to three independent experts for external peer review, in accordance with EPA's peer review guidelines. This EPA report contains documentation of the peer review process for the PQA-Ricardo study.

This document contains three components. First is the summary of the peer reviewer's comments and the response to those comments from EPA and/or Ricardo. Following this is the EPA charge letter to the peer reviewers which describes their task and what EPA requested from them in terms of deliverables. Lastly, is the peer reviewers submitted biographies and their comments on the draft PQA-Ricardo report.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ANN ARBOR, MI 48105

OFFICE OF
AIR AND RADIATION

DATE: January 16, 2008

MEMORANDUM

SUBJECT: EPA Response to Comments on Ricardo report entitled "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies", Draft Final Report by peer reviewers Dennis Assanis, Chinu Bhavsar and Ron Graves

FROM: Matt Brusstar, Advanced Testing Division
Ben Ellies, Transportation and Climate Division
Dave Haugen, ATD, Technology Development Group Manager

Dennis Assanis (of Assanis & Associates, Inc.), Chinu Bhavsar (formerly of Ford Motor Company) and Ron Graves (of Oak Ridge National Laboratory) reviewed Ricardo's report entitled "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies, Draft Final Report, November 2007".

This memo includes a summary of comments and responses and actions to comments from EPA and Ricardo.

Comment: There were multiple comments about the executive summary lacking a discussion of results or conclusions drawn from the data, for example: *"There should be more words summarizing the results (e.g., provide ranges of benefits), and assessing them critically (e.g., which technologies seem to incrementally or additively contribute the most), rather than just stating that the results are in the table below."*

> **EPA's Response:** EPA and Ricardo discussed this before undertaking this work and agreed that the report would include only objective simulation results, without any subjective recommendations or conclusions.

Comment: Multiple reviewers questioned why hybrid-electric vehicles (HEVs) were not part of the Ricardo study.

> **EPA's Response:** Hybrid technologies are showing dramatic improvements in GHG reduction, as reflected by every major auto manufacturer's plans to introduce some form of hybrid-electric vehicle. This major new group of drivetrain technologies are very complex,

both to integrate into vehicles and to simulate through vehicle simulation models. Because of the limited time and resources available for this study, any vehicle simulation of GHG reductions from hybrid electric vehicles will be necessarily conducted in another, subsequent study.

Comment: One reviewer mentioned that biofuels were not considered in this study.

EPA's Response: Although biofuels, renewable fuels and some alternative fuels have the potential to reduce GHG pollution, those benefits are realized primarily in their production rather than their consumption. Generally speaking, a vehicle powered on biofuels will not exhibit a significant reduction in *tailpipe* GHG emissions unless the vehicle is optimized for that fuel. Since there is very limited retail distribution network for fuels other than gasoline and diesel, within the near future it is unlikely that auto makers will manufacturer vehicles optimized for renewable fuels. Thus, the scope of this work is focused on vehicle fuels which are likely to be distributed nationally in broad and significant volumes.

Comment: Multiple reviewers commented: *"…the mostly-uniformly applied reductions in aero drag and rolling resistance are without supporting data or analysis. Perhaps this is covered in another study, but is conspicuously lacking the rigor of the remainder of the analysis. Aero and rolling loss factors for trucks are different than cars. Why?"*

"… what is the justification for the aero and rolling drag factors?"

"…If there is data to support these assumptions, it should be included in the report."

EPA's Response: To the extent that Ricardo was directed to evaluate representative vehicles in five vehicle classes, rather than the opportunities for improvement in individual and specific vehicles, a uniform reduction in aero-drag and rolling resistance were seen as the most appropriate means to project the gains available from these two technologies.

A vehicle's size and shape determine the amount of power needed to push the vehicle through the air at different speeds. Changes in vehicle shape or frontal area can therefore reduce GHG emissions. Areas for potential aerodynamic drag improvements include reduced frontal area as well as addition of skirts, air dams, underbody covers, and more aerodynamic side view mirrors. The technical literature consistently estimates that these design changes can provide at least a 10% improvement in aerodynamic drag coefficient in passenger cars, whereas 6%-10% Cd reduction is more realistic for trucks. Combining these drag coefficient improvements with a reduced frontal area equates to GHG reductions of 2% and 3% for trucks and cars, respectively. These numbers are in agreement with the technical literature and are supported by confidential manufacturer information.

Based on a 2006 NAS/NRC report, a 10% rolling resistance reduction would provide a GHG emissions reduction of 1 to 2 percent – and at this level the tires would maintain similar traction and handling characteristics. Again, these numbers are in agreement with the technical literature and generally supported by confidential manufacturer information.

Comment: A question raised was about the test cycles used for simulation: *"Why the UDDS instead of LA92 cycles? Show example to indicate degree of sensitivity to drive cycle for representative technology package (LA92, for example, vs. UDDS)."*

EPA's Response: Although EPA recently extended the fuel economy labeling methodology to 5 test cycles, most of the technology effectiveness data available today is based on EPA's Urban and Highway Driving Schedule Tests. Extending this report to incorporate EPA's 5-cycles used in fuel economy labeling would have extended the deliverable date of the report beyond that where it could be used in EPA's anticipated rulemaking process.

Comment: *"The report would be additionally instructive if the effect of reduced performance on CO2 emissions was shown for some example vehicles.*

EPA's Response: The objective of this study was to estimate the GHG emissions reduction potential of technology packages while constraining the vehicles to performance levels **equivalent** to the baseline vehicles. Acknowledging that manufacturers might choose to trade performance against cost in achieving GHG reductions, EPA has assessed technologies without this performance-cost trade-off, and thus the reviewer's comment highlights further reduction potential which was deemed beyond the scope of work at the time the report was commissioned.

Comment: *"What is the convention for the technology package identifiers? It is not intuitive (i.e. Z, 1, 15, 15a, 15b, etc.?)."*

EPA's Response: EPA provided Ricardo with technology packages and included identifiers for each package that were arbitrarily chosen for project management purposes. It would be errant to assume the identifiers have any meaning whatsoever.

Comment: Multiple reviewers questioned along the lines of: *"Page 6: The friction-reduction factor is consistent for all technology packages, in spite of the technology packages using different sized engines."*

EPA's Response: The engine friction reduction factor was provided by EPA as a general input representing reasonable fuel efficiency improvements applicable to all engines. It includes not only the effects of engine friction reduction, but also the use of lower-friction lubricants.

Comment: *"Most of the technology options explored seem to favor gasoline packages over diesels. The presentation of the results in chapter 7 selects four categories, all for gasoline engines, creating the appearance of imbalance"*

EPA's Response: Currently, diesels represent less than 1% of the light-duty market in the United States, although more stringent GHG and/or fuel economy regulations will certainly encourage increases in diesel market penetration. EPA feels that given all the technologies considered, diesels were adequately represented in terms of options available to reduce GHG emissions using conventional fuels. EPA is comfortable with Ricardo's presentation in chapter 7's highlight of the synergies between independent technologies when packaged on the same engine.

Comment: *"The reference and use of a "known factor" for every fuel, mentioned in section 2.10.2 to derive CO2 benefits from fuel economy results, is confusing. It would be desirable to show the analysis behind the 'known factor" that was used to convert fuel consumption savings to vehicle CO2 equivalent output—do these include upstream CO2 factors, or the effect of CH4 emissions? A brief discussion of the sources of uncertainty associated with the use of this factor equivalent should be added."*

EPA's Response: EPA provided Ricardo with constant tailpipe GHG conversion rates (that include contributions of CH4) which Ricardo applied to consumption of gasoline and diesel fuels in the simulated test cycles. These numbers are based on outputs from the Department of Energy's GREET model and do not include upstream CO2 factors (GHG emitted during production of the fuel). The intent of this project was to evaluate the effects of vehicle technologies with common fuels (rather than to investigate variability in the fuels themselves).

Comment: *"It should be mentioned that these might be market dependent. In European and Japanese markets where they have low sulfur and better quality fuels and different customer performance expectations (than US), it may be possible to deploy certain advance technologies earlier than the US."*

EPA's Response: Ricardo's technology readiness estimates described in the report are implicitly for the U.S. market only.

Comment: "*The focus on homogeneous stoichiometric GDI, at the request of EPA, seems to be unnecessarily too restrictive. Also, it is questionable whether a 1.5 increase in compression ratio can be realized without partial stratified, lean operation with GDI*."

EPA's Response:

a) EPA is unaware of any demonstrated technical pathway for meeting Tier 2 emissions levels with a lean combustion gasoline system, given the potential sulfur levels in gasoline in today's U.S. market. In absence of requirements for lower-sulfur gasoline, we believe it will be quite difficult to make a stratified lean-burn GDI "Bin 5" vehicle to the U.S. market in the near-term.

b) EPA defers to Ricardo's technical expertise in this area, but recognizes that this level of compression ratio increase is consistent with GDI engines available today.

Comment: *”Technology options are quantized into discrete bins, when in fact we could very well see in production hybrid versions of the options much sooner (e.g., GDI/HCCI dual-mode).”*

EPA’s Response: A prime objective of this study was to quantify the synergies and effectiveness of representative mechanisms, rather than explore specific realizations of specific mechanisms. In this case, Ricardo modeled the HCCI packages with only a limited HCCI operating range, outside of which they operated as spark ignition GDI engines so these technologies actually were considered as “hybrid” versions of HCCI as suggested by the reviewer.

Comment: *“There should have been a mention of the cam torque actuated phaser system in section 5.1.1. This type of phaser provides fast response and reduces energy consumption.”*

EPA’s Response: A prime objective of this study was to quantify the synergies and effectiveness of representative mechanisms, rather than explore specific realizations of specific mechanisms. EPA is aware of this specific form of variable valve timing and recognizes there are likely to be various implementations of each technology which cannot all be represented individually in the scope of this work.

Comment: *“Cylinder deactivation operating zone (section 3.3) would be dependent on the number of cylinders and engine displacement to vehicle weight ratio. As such those parameters should be incorporated in a detailed analysis.”*

EPA’s Response: EPA agrees and commissioned this report with this level of detail in mind. Ricardo built an individual vehicle simulation model for each technology package and vehicle combination. Thus, EPA accepts that these dependencies are accounted for in the results.

Comment: *”Table 1-1 and Table 1-2 have conflicting clutches for technology package Z (one is a dry clutch; the other is a wet clutch)…”*

EPA’s Response: Both of the “Z” technology packages have a dual-clutch transmission. The specific type of DCT is a further detail which, although resulting in different levels of transmission efficiency, was not intended to confuse the reader. Several technologies, for example wet clutch DCTs and dry clutch DCTs, are applied differently between vehicle classes. In this case, Ricardo confirmed that a dry clutch DCT is an appropriate design for the standard car, while the wet clutch DCT is appropriate for other vehicle classes.

Comment: *”What does it mean to “consider” NVH, but not quantify it?”*

EPA’s Response: The level of customer-accepted NVH is a subjective measure that is not subject to accepted industry-wide measurements techniques, metric quantifications and uniformly accepted levels. EPA requested that Ricardo use engineering judgment based on their vast experience in providing this form of NVH engineering services to the automotive industry to highlight any technology implementation that might cause a degradation in NVH that would be objectionable to the driver.

Comment: *"Page 49: The stated BMEP limits for naturally aspirated (13.5 bar) and boosted (in excess of 20 bars) engines seem too high for automotive applications…"*

EPA's Response: Recent market data confirms Ricardo's use of these levels of BMEP. For example, Toyota's 3.5L engine (Lexus G350) is rated at 274 ft-lb of peak torque, which equates to about 13.5 bar BMEP for a naturally aspirated engine. Similarly, GM's turbocharged 2.0L engine (Solstice GXP) achieves 260 lb-ft of torque (or 22.1 bar BMEP).

Comment: *"P59. Diesel. The system shown in Fig 5-19 is only high-pressure (HP) loop EGR. A better balance between in-cylinder emissions and aftertreatment required may be achieved with HP plus low-pressure loop EGR. EGR loop catalysts may not be adequately effective to prevent fouling."*

EPA's Response: A prime objective of this study was to quantify the synergies and effectiveness of representative mechanisms, rather than explore specific realizations of specific mechanisms. The system shown represents the modeling approach used for the vehicle simulation results reported.

Comment: *"Page 2: What does "unadjusted" refer to in the statement: "The unadjusted results for the EPA city, highway, and combined cycles. . ."?"*

EPA's Response: The term "unadjusted" implies raw laboratory or unadjusted fuel economy results, as opposed to "adjusted" results which are modified to better reflect real-world driving conditions. Refer to 40 CFR 600.206 for further details.

Comment: *"Table 1-6 (and other corresponding tables): Define in the text what is meant by "FDR", especially since transmission technology variances include gearless systems such as CVTs."*

EPA's Response: FDR – or Final Drive Ratio – is applicable even to continuously variable transmissions. As is the case with a traditional step-gear transmission, the operating gear (or theoretical torque conversion) ratio of a CVT is then multiplied by the FDR to provide the overall vehicle driveline gear ratio.

Comment: Regarding Figure 4-5: "*Why are the CO2 output levels for the base simulated vehicles not compared against the actual values? This is done for the fuel economy numbers.*

EPA's Response: That calculation can be made by applying the gasoline GHG emissions factor to each of the baseline vehicles.

Comment: There were multiple comments on the effect of technologies on vehicle weight, and the treatment of vehicle weight in the study. For example: *"…Some technologies such as a diesel engine with a complicated emission control system could significantly affect vehicle weight with a corresponding negative effect on gas mileage and CO2 emission."*

"In general there seems to be inadequate attention or discussion about weight differences among the technology packages. Are we to assume that all engine and transmission options had same weights? At least there should be some discussion of this. Specific example: boosted, downsized engines, pp. 50-51"

> **Ricardo's Response:** *"The intent was to make the study weight-neutral to the extent that no vehicle would change ETW class. Downsizing of diesels will offset heavier aftertreatment and may result in lower vehicle weight."*

Comment: *"More discussion of uncertainties in the analysis should be presented along with the findings, to add perspective. The report should not characterize the study as "scientific" unless data uncertainty is discussed and shown (in appropriate situations). In a less rigorous manner, the authors should still address the uncertainty associated with critical assumptions."*

> **Ricardo's Response:** *"The study was performed in a scientific and consistent manner, based on accurate modeling of the physics involved. Uncertainties from the simulation method are negligible, but the variations in applying the technologies to a vehicle (i.e. differences in actual specification, design, and calibration) are much greater than can be projected for a class of vehicles."*

Comment: *"Although numerous publications are cited for data, much of the input data are held as proprietary and undisclosed. This could give rise to the results of the study being challenged. Ricardo has an excellent international reputation, but will it be sufficient to deflect doubts as to accuracy of input data and assumptions? An alternate would be to use more data from the public domain."*

> **Ricardo's Response:** *"Ricardo data is proprietary information and cannot be released to the public. However, Ricardo's libraries and experience spans the world's manufacturers and product lines. Further, Ricardo used as much public-domain information as possible in the study. However, there was insufficient data available for the detailed simulation performed and so it was supplemented and verified against Ricardo proprietary data."*

Comment: *"Page 28: What is the "BSFC modifier" based on?"*

> **Ricardo's Response:** *"It is based on proprietary Ricardo data."*

Comment: *"Page 28: It appears as though the simulation neglects the electrical loads on the alternator system when the radiator uses an electric fan (as is the case in all nontruck vehicles). Please clarify."*

Ricardo's Response: *"These loads were included in the base vehicle electrical load and so were included for all cases with electric fan in the base configuration."*

Comment: *"Page 35: the statement that the comparison simulated and actual vehicle results shows "noticeable difference" is too subjective (there is a "noticeable difference" in* all *of them). Given the challenges involved in generating consistently rigorous sets of data for all cases and various subjective assumptions involved in the analysis, please correct the language and use appropriate words other than "scientific" and "significant"."*

Ricardo's Response: *"The study was performed in a scientific and consistent manner, based on accurate modeling of the physics involved. However, the differences between the simulation results and measured data are largely due to differences between the input data which attempts to describe an average vehicle and, in some cases, measurements from an individual vehicle."*

Comment: *"P40. It would be useful to see the BSFC data that show the impact of cam phasers, said to be widely used. Hence the data should be relatively non-sensitive. Similarly, the valve control options are seen later as having major impact on fuel efficiency. The lack of supporting data in the report leaves the reader questioning the results."*

Ricardo's Response: *"While the technology might be widely used, this is Ricardo proprietary data and cannot be shared. Ricardo invests significant time and effort in benchmarking the industry to obtain this data."*

Comment: *"Figure 3-3 (and other corresponding figures): Why do required power curves become constant at a certain speed for various loads? Does the heat removal with oil flow not increase with speed after a certain point?"*

Ricardo's Response: *"Heat removal does not increase above a certain speed because the oil flow from a conventional pump is limited by a pressure regulator. Although the conventional pump power continues to increase with speed, the flow through the engine does not."*

Comment: "Page 82: This "torque-to-weight" ratio is very confusing, and doesn't really contribute any meaning to the study. This review suggests you remove it (and its corresponding figure) from the discussion."

Ricardo's Response: *"The torque-to-weight ratio relates to the load levels that the engine runs at on a drive cycle, hence vehicles with a low torque-to-weight ratio will run at higher engine loads and so benefit less from camless technology."*

Comment: *"Table 7-9. We have seen diesel applications in prototype light trucks getting 35-50% higher "tank mileage" than SI with similar performance (published). 20% gain seems very conservative. With good PCCI systems, we should see aftertreatment penalties closer to 3%. Consider including a simple explanation why 20% is the correct value in view of more optimistic published reports."*

Ricardo's Response: *"The transmission was not changed and so the diesel engine operating points were not optimized. Refer to the discussion in Sec 7.2 and the footnote at the bottom of the table stating that optimization was not performed for each step."*

Comment: *"Engine up shift RPM for a V8 (p 26) appears to be too high. I believe this needs to be rechecked."*

Ricardo's Response: *"P. 28 shows min speed for V8 upshift to be 1150rpm. This may vary based on vehicle stiffness but it is not out of line with industry practice."*

Comment: *"The fuel economy/CO2 benefits of a camless valvetrain depend on the power consumption of the camless system as well as the operating domain (cylinder deactivation, six cycle etc). These parameters should have been used for modeling and included in the report."*

Ricardo's Response: *"Sec 5.1.7 discusses the power consumption issue, and sec 5.1.7.1 discusses the operating domains enabled with camless. Sec 5.1.7.2 and 5.1.7.3 discuss the source of the data (published) and the power consumption issue again. Additionally, Sec 7.3 specifically calls out camless and HCCI as low readiness technologies requiring long-term development."*

Comment: *"Section 3.4: It is assumed that electric power steering consumes no steering input on the EPA drive cycle and therefore that there is no parasitic loss from it. This is true, but there has to be some adjustment for generating electric energy for steering use. The electric energy consumed in steering will have an undetermined negative impact on fuel economy/CO2."*

Ricardo's Response: *"The reviewer is correct that there will be an undertermined negative impact on FE/CO2, depending on the amount of steering done. Unless the amount of steering input is defined we cannot determine the impact. This study only considered the EPA city and hiwhway cycles and straight-ahead accelerations, so no steering inputs were included. They would be of off-center steering inputs. In addition, the parasitic loss from the PS pump during straight ahead driving offsets the negative impact of the electrically-driven pump."*

Comment: *"To a technical reader, Tables 7-5 through 7-9 are some of the more interesting. How much influence is there from the sequence in which technologies are added?"*

Ricardo's Response: *"Ricardo did not examine any other sequences for technology additions than those prescribed by EPA already stated in the study, so we cannot quantify the influence.*

EPA's Response: The affect of technology-pairing and its accounting in a technology application sequence is an interesting and relevant issue that EPA intends to address in subsequent work.

Comment: *"P 30- Start Stop model. The model or strategy appears to hinge on coolant temperature as the principal signal to manage the on-off cycle. Is it well-established that the coolant temperature is indicative of the exhaust catalyst temp that is so crucial for emission controls? I would have thought a catalyst temp monitor would have been desired."*

Ricardo's Response: *"(Coolant temperature) is indicative of exhaust temperature but there are other considerations that make using catalyst temperature (undesirable). Specifically, the coolant temperature is slower to warm up than catalyst temperature and so the engine should not be shut off until up to a minimum (coolant) temperature.*

Comment: *"P60. Did the engine-out NOx map include much operation in PCCI modes? What fraction of operating range? The 60-75% LNT reduction may be a bit high for a very effective PCCI engine."*

Ricardo's Response: *"PCCI was not used in the maps and that is why 60-75% effectiveness is stated. With aggressive application of PCCI not as much aftertreatment would be required and the fuel penalty would be lower."*

Comment: *"P62. The 550C regeneration temperature for DPF is rather high if a catalyzed device is used. Balance point temps are more like 350C. Would this lower the fuel penalty in the simulation?"*

Ricardo's Response: *""The 550°C regeneration temperature is to facilitate active regeneration, whereby extra hydrocarbons are used to trigger a regeneration event. ""Balance point"" is a term useful for catalyzed DPF systems where there is continuous passive regeneration of the DPF, usually by the reaction of NO2 with the carbon in the DPF. While a 350°C balance point temperature seems reasonable; the usefulness of the metric is suspect because it depends greatly on the specific test protocol used to estimate it. (That is, what else changes when one changes exhaust gas temperature?) The expectation is that LDD systems need some active regeneration capability, especially if the DPF is downstream of the deNOx device."*

Comment: *"References to the methodology as "scientific" based on a "physics-based modeling approach" are somewhat misleading. The descriptors "scientific" and "physics-based' for the model must be reconciled with evidence to the contrary in the paper. For instance, in some cases, there are steady-state dyno test data behind an engine map featuring a certain technology. In other cases, available data were scaled based on empirical/proprietary factors (i.e., "BSFC modifiers" and "empirical formula derived from several transmissions"-p. 28, GHG-CO2 conversion factors). Please verify and correct the statements so as to create a realistic impression of the vehicle simulation."*

Ricardo's Response: "*The study was performed in a scientific and consistent manner, based on accurate modeling of the physics involved. The input data and maps were accumulated through several means, including test data and scaling of known quantities. Science can deal with empirical (measured) data as well as purely mathematically-derived data.*"

Comment: "*It would be helpful to include a summary that defines the theoretical boundaries for CO2 reduction potential for powertrains, i.e., what can be achieved if the engine operated at the best efficiency all of the time allowing for some degradation during the warm up period. This would form a basis for a quick check on the validity of combining various technologies*"

EPA's Response: The approach referred to above is used in the "lumped-parameter" technique of estimating impacts of multiple technologies (EPA used a similar approach in initially estimating technology synergies for its rule). The Ricardo modeling work was commissioned to validate EPA's preliminary estimates drawn from theoretical potentials, not vice versa. EPA intends to publish a technical document that explains and compares results generated from both the "lumped-parameter" technique and Ricardo's vehicle simulation results.

General Editorial Comments

The remaining comments were those consisting of an editorial nature (formatting and typographical suggestions). These comments, as appropriate, are reflected in Ricardo's final report. As such, these comments have not been addressed in this document.

Charge Letter Example:

November 2, 2007

Peer Reviewer
(address)

Dear Peer Reviewer:

Thank you for agreeing to review the paper entitled *A Study of the Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies*, October 2007, prepared by PQA/Ricardo, Inc. The paper was prepared in support of the Greenhouse Gas Rulemaking (GHG). The vehicle modeling paper is enclosed.

We are working to continually improve estimates of GHG emission reduction from incorporation of technologies, and in this paper we were particularly interested in how particular technologies or technology packages differently affect different categories of automobiles. The five categories we examined include: small car, small MPV, large MPV, large car, small truck. Technologies include: variable valve train timing and lift systems, cylinder deactivation, turbocharged/down size engine, advanced transmission technologies, stop-start, diesel, etc. The performance criteria of the technology packages were compared to the performance criteria of current production vehicles through baseline modeling. Performance criteria such as “launch” 0-30 mph, “on-ramp” 30-50 mph, “traditional acceleration” 0-60 mph, “passing” 50-70 mph, sustained grade capability at cruise speed, transmission shifting business and other NVH issues, Tier 2-bin 5 emissions and FTP cycle CO2 emissions levels (also available in terms of MPG) were considered and matched as practicable in the simulations of the final packages. Also presented should be some incremental vehicle simulation runs, which should enable a better understand of the synergistic consequences of combining multiple technologies to reach more stringent vehicle GHG standards.

In regard to reviewing the enclosed report, please use the following criteria:

1) clarity/understandability,
2) reasonableness of methodology and assumptions,
3) appropriateness of data, and
4) recommendations for any alternate methodologies and/or data.

When making recommendations, please make a distinction between clearly defined improvements that can be readily made based on data reasonably at hand to EPA and improvements that are more exploratory or dependent on data not readily available to EPA. The comments should be sufficiently detailed to allow thorough understanding by EPA or other parties familiar with the work.

Your comments should be provided as an enclosure to a cover letter that clearly states your name, the name and address of your organization, what material was reviewed, a summary of your expertise and qualifications and a statement that you have no real or perceived conflicts of interest. The comments should be sent in care of Cheryl Caffrey to the following address:

U.S. EPA
Office of Transportation and Air Quality
Assessment and Standards Division
2000 Traverwood Drive
Ann Arbor, MI 48105

Also, send the cover letter and comments by e-mail to Cheryl Caffrey at caffrey.cheryl@epa.gov (provide comments in MS Word or a format that can be imported into MS Word so we can create a document that lists both your comments and our responses to these comments). Please do not provide the peer review materials or your comments to anyone else.

We would appreciate receiving the results of this peer review in the shortest time frame possible, preferably by November 16. If you have any questions about what is required in order to complete this review, or if you find you need additional background material, please contact Matt Brusstar by phone at (734)214-4791 or by the email at brusstar.matt@epa.gov .

As has been discussed with you, you will be paid a flat fee of $3,000 for this peer review. This fee was calculated based on an estimated 12 hours of review time at a rate of $250 per hour. In your cover letter, please indicate the number of hours spent on the review; spending fewer or more hours than our estimate will not affect the fee paid for this work, but will help us improve our future estimates. A purchase order form is also included hosing payment information. You may expect to receive payment in full within fourty-five (45) days of submitting your invoice and comments to Cheryl Caffrey.

Thank you again for your time and consideration.

Sincerely,

Dr. David Haugen, P.E.
Manager, Technology Development Group and
Deputy Director, Advanced Technology Division
National Vehicle and Fuel Emissions Laboratory
U.S. EPA's Office of Transportation and Air Quality
PHONE: (734) 214-4366; FAX: (734) 214-4573; EMAIL: haugen.david@epa.gov
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Enclosure

Reviewer Bio:

AAI

Assanis & Associates, Inc.

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December 4, 2007

Cheryl Caffrey
U.S. EPA
Office of Transportation and Air Quality
Assessment and Standards Division
2000 Traverwood Drive
Ann Arbor, MI 48105

Dear Cheryl:

With this cover letter you will find my comments on the paper entitled, *A Study of the Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies*, dated November 9, 2007. I received this report via email from EPA on November 9, 2007. The comments are organized according to the guidance in the November 2, 2007 transmittal letter signed by Dr. Haugen of EPA.

Also as requested, here is a brief summary of my qualifications, prepared as a third person biographical summary:

Dr. Assanis received the B.Sc. degree in Marine Engineering from Newcastle University, England in 1980, and four graduate degrees from the Massachusetts Institute of Technology: S.M. in Naval Architecture and Marine Engineering (1982), S.M. in Mechanical Engineering (1982), Ph.D. in Power and Propulsion (1985) and S.M. in Management from MIT's Sloan School of Management (1986). He has worked as Assistant and Associate Professor (with tenure) at the University of Illinois at Urbana-Champaign from 1985-1994. He joined The University of Michigan in 1994 as Professor of Mechanical Engineering. He has served as the Founding Director of the interdisciplinary graduate program in Automotive Engineering between 1996 and 2002, and subsequently as Chair of the Department of Mechanical Engineering from 2002-2007. In parallel, he has revitalized the Mechanical Engineering Department’s teaching and research efforts in internal combustion engines. He currently serves as the Director of the Automotive Research Center, the Director of the Walter E. Lay Automotive Laboratory, and the Director of the Multi-University Consortium on Homogeneous

Charge Compression Ignition Engine Research. He is also the Co-Director of the General Motors Collaborative Research Laboratory on Engine Systems. He is an international authority in the field of internal combustion engines, and has published over 250 articles in journals and international conference proceedings.
His expertise encompasses both modeling methodologies and experimental techniques for studies of the fundamental thermal, fluid and chemical phenomena that occur in advanced internal combustion engines and exhaust catalysts so as to develop systems with significantly improved fuel economy and dramatically reduced emissions. He is a Fellow of the Society of Automotive Engineers. He is an editorial board member of several journals and has organized or chaired over 60 sessions at international technical conferences. He is also the President of the engine consulting company Assanis & Associates, Inc.

As requested in the transmittal letter, I hereby affirm that I have no real or perceived conflict of interest as a reviewer of the subject report. I am pleased to have been given the opportunity to review this report and make a modest contribution to EPA's rulemaking process. Please feel free to contact me for clarifications on any of the review comments.

Sincerely,

Dennis N. Assanis

Enclosure:
Review comments on *A Study of the Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies,* dated November 9, 2007

Report Review on

"A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies"

Ricardo, Inc.
November 9, 2007

SUMMARY COMMENTS

The objective of this reported study is to identify the relative impact of novel and advanced vehicle technologies on fuel economy and greenhouse gases – specifically carbon dioxide (CO_2). The objective is pursued by comparing different "packages" of advanced vehicle technology using a model-based vehicle simulation software in conjunction with experimental data and empirical rules. Vehicles comprising five different platforms are evaluated. Representative vehicles from each platform are identified for relevance and for limited validation of the simulation predictions for the baseline case. In the spirit of improving the quality of the study and the report, the reviewer provides several general and detailed comments for consideration by the contracting agency and the authors of the report.

Overall, the report attempts to undertake an analytical technology assessment study of significant scope in a short amount of time. It does a fairly competent job at analyzing a select number of technologies and packages, mostly aimed at improving the gasoline IC engine and to a less extent the diesel engine. However, several promising technologies and fuel options for IC engine technologies (other than gasoline and diesel) which can make a significant contribution to the improvement of mpg and reduction of CO_2 emissions have not been considered, or even mentioned at all. A primary example of this is the hybridization of gasoline engines (other than mild start/stop options) which is in production today, achieving significant CO_2 benefits. Another major omission is any mention of biofuels, which from the standpoint of a life cycle analysis have strong potential for reduction of CO_2 emissions and CO_2 sequestration.

As it is, the executive summary of the report is not adding much value to the entire document. It merely recycles tabulated results that are repeated in other chapters of the document in exactly the same form, without any attempt of summarizing key findings for the reader. On the other hand, it goes into great length to provide disclaimers of what Ricardo was tasked to do and not to do. There is a place for this, such as in a preface, but the executive summary should provide to the reader a concise synopsis of the scope, the approach followed and the major fact findings – while being sensitive to not drawing conclusions. I recommend that all detailed tabulated results should be in the appendix, listed once and referenced throughout the report. I would also like to see a consistent and high-level "train of thought" throughout the summary with some very specific statements and reasoning for narrowing down the technology and fuel options to the ones selected.

In general, the report is unnecessarily lengthy at places, while too laconic at other places. The draft can definitely benefit from re-organization and better balancing of its chapters.

There is unnecessary duplication of tables that can be in the appendix and referenced. The reviewer attempts to point out further opportunities for shortening the report in the section providing “Detailed Comments”. On the other hand, Chapters 4 and 6 are very skinny and should be merged with other chapters. There should be more words summarizing the results (e.g., provide ranges of benefits), and assessing them critically (e.g., which technologies seem to incrementally or additively contribute the most), rather than just stating that the results are in the table below. More discussion of uncertainties present in the analysis should be presented along with specific findings so as to enable the reader to place the findings into proper perspective. In general, figures were not introduced in the text in the style they should. All figures and tables should be explicitly referred to and discussed in the text. Furthermore, figures must be identified by their figure number, not their relative position to the text. For example, Page 52 states “Typical cylinder pressure diagrams for recompression HCCI are provided in the first figure below.”

References to the methodology as “scientific” based on a “physics-based modeling approach” are somewhat misleading. The afore-quoted statements suggest that the simulation is composed of rigorous, first-principle expressions for the various phenomena without using “correlations”, “empirical formulas”, and “phenomenological models”. Are these conditions truly met? Certain clues indicate that the latter is not the case. For instance, in some cases, there are steady-state dyno test data behind an engine map featuring a certain technology. In other cases, available data were scaled based on empirical/proprietary factors. For example, page 28 states “the models applies a BSFC modifier”, page 21 gives a multiplier factor for CO_2 emissions, and page 28 states “based on an empirical formula derived from several transmissions. . . “. Please verify and correct the statements so as to create a realistic impression of the vehicle simulation.

Related, and perhaps more important, the report should not characterize the study as “scientific” unless data uncertainty is discussed and shown (in appropriate situations). To be completely rigorous, no data can be claimed to be relevant or significant unless there is a way to quantify uncertainty. Realizing that this study does not probably need to go into such rigor, the author(s) should still address the uncertainty associated with critical assumptions. For example, page 35 states that the comparison between simulated and actual vehicle performs shows “noticeable difference”. This reviewer also sees a “noticeable difference” in all of the listed fuel economies. Whether these “noticeable differences” are significant or not is presently indeterminable. Given the challenges involved in generating consistently rigorous sets of data for all cases and various subjective assumptions involved in the analysis, please correct the language and use appropriate words other than “scientific” and “significant”.

The author(s) occasionally write(s) in past tense. The report could be written in present tense (unless referring to specific actions that took place in the past, such as, “the engine was operated at x speed and y load”). A reader will always be reading the report in the present.

GENERAL TECHNICAL COMMENTS

In certain cases, technology options are quantized into discrete bins, when in fact we could very well see in production hybrid versions of the options much sooner. For instance, GDI/HCCI employing spark-ignition for part of the range (start-up and high load) and HCCI combustion mode for all other regimes. In many ways, HCCI is a combustion mode that can be realized through the integration of several of the technology packages presented and should not be viewed as a strap-on option. While camless is one way to enable HCCI (and will require a longer time horizon), HCCI can be realized via the use of cam profile switching/phasing and mechanical lift control. This is acknowledged in the report under the HCCI technology discussion of Chapter 5. If this option were to be pursued, the claimed benefits of the mechanical VVA systems can be augmented. At present, it is not clear which of the possible benefits of the VVA packages have been harnessed in each case (improvement of volumetric efficiency, elimination/reduction of throttling to reduce pumping losses, cylinder deactivation to reduce pumping losses, compression ratio variation to increase fuel economy and avoid knock, alteration of the combustion process by modulating trapped residual, etc). Overall, a more systematic analysis of technology package combinations is warranted as several are synergistic but not additive. Section 7.2 acknowledges this fact and is a start, but falls short of doing a comprehensive analysis.

While diesels are considered as an optional package, most of the technology options explored seem to favor the gasoline package. Furthermore, the results of chapter 7 present selected results in four categories, seemingly all for gasoline engines. This creates the appearance of imbalance.

The reference and use of a “known factor” for every fuel, mentioned in section 2.10.2 to derive CO_2 benefits from fuel economy results, is confusing. It would be desirable to show the analysis behind the ‘known factor” that was used to convert fuel consumption savings to vehicle CO_2 equivalent output. Do these CO_2 equivalent emissions include the CO_2 released during the production of the respective fuels, or just the use (i.e. combustion) of the respective fuels? If the latter, different engine technologies may yield different combustion efficiencies and methane concentrations (which could be significantly different than the values reported in Table 2-8). Some language should be added to the report to identify the sources of uncertainty associated with the use of this factor equivalent.

The focus on homogeneous stoichiometric GDI, at the request of EPA, seems to be unnecessarily too restrictive. Some GDI engines in production operate under the lean stratified mode when at part-load conditions, yet operate at homogenous stoichiometric conditions when requiring full power. This report seems to suggest that GDI engines operate with “one or the other” strategy, which limits the technology benefit to the identified charge cooling effect. Would the charge cooling effect alone really offer up to a 1.5 times increase in compression ratio? It is more plausible that the combined effects of stratified charge, lean mixture, and cooling effect could result in this benefit.

DETAILED COMMENTS

• Table of contents is missing the "front matter" contents (i.e. title page, table of contents, list of figures, etc).

• Example of past tense language: Page 1, "Vehicle performance metrics were considered an important part. . . "

• Inconsistency observed between CO_2 and CO2.

• A clear objective is not stated in the Executive Summary. The motivation for this study as listed on Page 1 conflicts with the motivation listed on Page 13. Page 1 states "The intended purpose of this study is to serve as an input to the EPA in its rule-making effort. . ." while Page 13 states "To overcome the limitations of the previous studies, the objective of the present study. . ."

• Page 2: What does "unadjusted" refer to in the statement "The unadjusted results for the EPA city, highway, and combined cycles. . ."?

• Page 3: It is not clear if there are two time-ratings or three time-ratings. Are the time ratings 1) in production now, 2) in production in 5 years, and 3) in production in 10 years? Or are the time ratings 1) in production now, and 2) in production in 5 – 10 years?

• What is the convention for the technology package identifiers? It is not intuitive (i.e. Z, 1, 15, 15a, 15b, etc.?).

• Table 1-1 and Table 1-2 have conflicting clutches for technology package Z (one is a dry clutch; the other is a wet clutch). This error exists in similar tables where the technology package is described.

• Page 6: The friction-reduction factor is consistent for all technology packages, in spite of the technology packages using different sized engines.

• Page 6: ". . .tables to distinguish their higher level of uncertainty. . .": how is uncertainty quantified?

• Table 1-6 (and other corresponding tables): Define in the text what is meant by "FDR", especially since transmission technology variances include gearless systems such as CVTs.

• Table 1-6 (and other corresponding tables): Should "Distance at 3 sec" be provided in units of miles (as opposed to meters), since the base convention used throughout is English system of units (the obvious and appropriate exception being g/mile of emissions).

• Page 13, in the first statement under section 2.3: Correct "the modeling approached used” to “modeling approach”. Also, change “forward-facing” to “forward-looking” which is more standard terminology and to be consistent with what is mentioned in page 1.

• Page 13: What does it mean to “include torques”, as mentioned in the statement “The model physics includes torques. . .”

• Page 14: Can Tables 2-1 and 2-2 be combined, and perhaps orientated in landscape fashion to conserve space (or at least be easier on the reader)?

• Table 2-3 (and other corresponding tables): Can’t the column headers be orientated horizontally, for ease on the reader (and create less white space).

• Page 21: For convenience to the reader, please describe in more detail what the EPA’s “ETW” is, and how it is calculated.

• Page 28: What is the “BSFC modifier” based on?

• Page 28: It appears as though the simulation neglects the electrical loads on the alternator system when the radiator uses an electric fan (as is the case in all nontruck vehicles). Please clarify.

• Page 28: What does it mean to “consider” NVH, but not quantify it?

• Page 30 (and other instances): Should the 42V / 14V transformer be referred to such, as opposed to “DC-DC converter”?

• Page 30: Example of past tense, “The 42V stop-start included. . . “

• Page 31: Replace statement that reads “It is assumed that the energy. . .” with “It is shown that the energy . . .” since you actually run a computation to verify this.

• Page 31: In the statement that reads “requiring less that 1 kJ”, replace “that” with “than”.

• Figure 3-2 (and other corresponding figures): Please define AC drive efficiency, and why it is seemingly used as a metric for these components.

• Figure 3-3 (and other corresponding figures): The legend is confusing, and 75% required power legend identifier is unclear.

• Figure 3-3 (and other corresponding figures): Why do required power curves become constant at a certain speed for various loads? Does the heat removal with oil flow not increase with speed after a certain point?

• Figure 3-5: Cannot read y-axis label.

• Figure 4-5: Why are the CO_2 output levels for the base simulated vehicles not compared against the actual values? This is done for the fuel economy numbers.

• Page 39-40: Should benefits to reduction of other emissions be identified if it is not part of the objective of this study? It seems to only be done for cam phaser technology; the implications of other technologies on NO_x and HC emissions are not discussed.

• Figure 5-3 (valve profile) is unclear.

• Page 46, statement that reads "No major changes to engine architecture are required compared to a port fuel injection engine": Is this statement really true? Don't you have to add a high pressure fuel injection system?

• Page 49: The stated BMEP limits for naturally aspirated (13.5 bar) and boosted (in excess of 20 bars) engines seem too high for automotive applications. Perhaps for 15L heavy-duty turbocharged diesel engines it is possible to reach 20 bar BMEP, however this reviewer believes a number closer to 12 bar BMEP is appropriate for full load turbocharged diesel automotive engines.

• Page 49: What is the final paper number of the quoted SAE paper? Currently, the "accepted abstract" paper number is cited.

• Figure 5-10 is an excellent example of how uncertainty bars on the data can indicate to the reader where differences in BSFC become significant.

• Figure 5-11: Perhaps re-orientate the legend so that "Turbo SIDI I4" reads over top of its corresponding data set (and same is true then for "NA V8").

• Page 52: Leave out the statement that reads "HCCI is also known as . . .". The current "name count" of HCCI combustion is over 20.

• Figures 5-14 – 5-16. Why are these figures in the report? They are not discussed in the text and really don't contribute anything to the discussion.

• Page 58: The reviewer suggests to change the statement "Diesel engines gain efficiency through high compression ratios and significantly reduced throttling or pumping losses" to "Compression ignition, diesel engines enjoy an efficiency advantage compared to spark-ignition engines due to their higher compression ratios, and overall fuel lean, unthrottled operation."

• Figure 5-19 (and other corresponding figures): A throttle is not listed in the text. While it is assumed that the throttle is used to help control EGR flow, it should either be discussed as such in the text or be removed from the figure so as to not mislead the reader about diesel engines.

- Page 66 contains too much white space.

- Figure 5-25 through Figure 5-27 are too small.

- Tables 7-1 (and other corresponding tables): Why are the base conditions not provided for comparison to the performance data?

- Page 82: This “torque-to-weight” ratio is very confusing, and doesn’t really contribute any meaning to the study. This review suggests you remove it (and its corresponding figure) from the discussion.

- Page 84: Statement that reads “The effect on fuel economy and CO_2. .. “ should be pluralized.

Reviewer Bio:

November 16, 2007
Chinu Bhavsar
1415 Packard
Ann Arbor, Mi 48104

To:
U.S. EPA
Office of Transportation and Air Quality
Assessment and Standards Division
2000 Traverwood Drive
Ann Arbor, Mi 48105
Attn: Ms. Cheryl Caffrey

Subject: Review of the paper entitled *A Study of the Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies*, Draft dated November 9 2007, prepared by PQA/Ricardo,

Dear Ms. Caffrey

In response to the EPA purchase order EP08B000029 for peer review of the subject report, and Dr. David Haugen's letter dated November 2, 2007, I am submitting my comments and recommendations per the attached document.

I feel that I have the right experience and qualifications to review the subject report. Here is a brief summary of my qualifications and expertise.

I am a retired engineer with MS degree in Mechanical Engineering from Stanford University. I worked at Ford Motor Company for 36 years prior to my retirement in October 2005. I spent most of these years at Ford on developing advanced and research powertrain (Engine & Transmission) technologies. Of those years around 5 were spent on vehicle performance and fuel economy modeling methodologies. I also chaired Ford's powertrain Fuel Economy Forum the purpose of which was to monitor and prioritize engine, transmission and vehicle technologies that improve vehicle fuel economy and reduce GHG emissions.

At the present time I am retired and I have no real or perceived conflict of interest that could possibly affect my analysis and review of the subject paper.

I have spent a total of eighteen (18) hours to review the paper and provide my comments

Thank you for giving me the opportunity to review the paper.

Sincerely,
Chinu Bhavsar
Tel: 734-678-1096 or 734-663-5861
Email:cpbhavsar@comcast.net

REVIEW OF THE PAPER ENTITLED

A STUDY OF THE POTENTIAL EFFECTIVENESS OF CARBON DIOXIDE REDUCING VEHICLE TECHNOLOGIES, DRAFT DATED NOV 2007 BY PQA/RICARDO INC.

(By: Chinu Bhavsar)

Introduction: This report is being provided to EPA in response to a purchase order request from EPA to review the subject paper and provide comments. I have reviewed the paper and offer the following comments.

Clarity/understandability

There is a large volume of detailed and reasonably accurate information in the report. It appears that Ricardo Inc. has used excellent modeling and analytical methods to predict vehicle CO2 emissions and performance for the various technology bundles EPA requested.

I suggest that the report could further be improved to make it more concise and comprehensible. It is my opinion there is too much information in the body of the report; some of it is redundant and the report could be better organized to make it more presentable.

Here are my specific recommendations and comments for each section of the report

Executive summary: Pages 7 thru 11: Show CO2 benefit for only one FDR for each package identified by EPA. There is no need to clutter the executive summary with all of the details for various FDR's. Those details are already and should be only in the appendix. Removing FDR details would have no significant impact on the findings of the report

Pages 14-15 combine tables 2-1 and 2-2. There is no need to repeat information from table 2-1 in table2-2

Pages 16 through 20 FDR rows could be eliminated by stating, "Various FDR's were used"

Pages 36 & 37 can be eliminated or moved to the appendix. Page 38 (fig 4-5) is sufficient to indicate that the modeling used correlates very well with the test data.

Section 5.0: most of the description of individual technologies should be moved to the appendix. This is like an encyclopedia of advanced powertrain technologies. Only the relevant data (source of efficiency maps, maps & logic used for modeling etc) should be left in section 5.0.

There should have been a mention of the can torque actuated phaser system in section 5.1.1 this type of phaser provides fast response and reduces energy consumption

Section 6.0: Technology readiness estimates: It should be mentioned that these might be market dependent. In European and Japanese markets where they have low sulfur and better quality fuels and different customer performance expectations (than US), it may be possible to deploy certain advance technologies earlier than the US.

Section 7.0 Show only CO_2 benefit and move fuel economy to the appendix.

Reasonableness of methodology and assumptions.

Ricardo appears to have used state of the art methodology to conduct vehicle CO_2 emission and performance predictions. They have used appropriate parameters and constraints to define acceptable operating zones for various technologies. However, I am not clear on one topic. Did the analysis include the effect each technology had on vehicle weight? Some technologies such as a diesel engine with a complicated emission control system could significantly affect vehicle weight with a corresponding negative effect on gas mileage and CO_2 emission.

Cylinder deactivation operating zone (section 3.3) would be dependent on the number of cylinders and engine displacement to vehicle weight ratio. As such those parameters should be incorporated in a detailed analysis.

Engine up shift RPM for a V8 (p 26) appears to be too high. I believe this needs to be rechecked.

The fuel economy/CO_2 benefits of a camless valvetrain depend on the power consumption of the camless system as well as the operating domain (cylinder deactivation, six cycle etc). These parameters should have been used for modeling and included in the report.

Section 3.4: It is assumed that electric power steering consumes no steering input on the EPA drive cycle and therefore that there is no parasitic loss from it. This is true, but there has to be some adjustment for generating electric energy for steering use. The electric energy consumed in steering will have an undetermined negative impact on fuel economy/CO_2

Appropriateness of data

Ricardo has used in house benchmark data and technology development data where available. They have used data from external sources when they did not have internal data. This is very appropriate

Since I do not have access to the Ricardo in house data, I am not in a position to judge the quality of such data. But I would like to state that the results of the analysis in some cases produce higher fuel economy/CO_2 benefits than my experience would indicate. I recommend that the results for the following packages be rechecked

Package Z for Standard vehicle class

Package 16 for full size vehicle class

Package 6b for large MPV vehicle class

Package 10 for truck vehicle class

Section 6.1.1 & 6.1.2 Data supplied by EPA: If there is data to support these assumptions, it should be included in the report.

Recommendations for any alternate methodologies and /or data

It would be helpful to include a summary that defines the theoretical boundaries for CO2 reduction potential for powertrains. I.e. what can be achieved if the engine operated at the best efficiency all of the time allowing for some degradation during the warm up period. This would form a basis for a quick check on the validity of combining various technologies.

Conclusion: The quality and content of the report are excellent. Certain modifications in the presentation of the analysis and results are recommended to improve clarity and understanding. Without these changes the report is difficult to follow even for a person well informed on the topic.

This review has been for prepared for EPA and submitted to them on Nov 16th, 2009 by:

Chinu Bhavsar, a retired automotive engineer

1415 Packard

Ann Arbor, MI 48104

Reviewer Bio

Cheryl Caffrey
U.S. EPA
Office of Transportation and Air Quality
Assessment and Standards Division
2000 Traverwood Drive
Ann Arbor, MI 48105

Dear Cheryl:

With this cover letter you will find my comments on the paper entitled, *A Study of the Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies*, dated November 9, 2007. I received this report via email from EPA on November 9, 2007. The comments are organized according to the guidance in the November 2, 2007 transmittal letter signed by Dr. Haugen of EPA.

Also as requested, here is a brief summary of my qualifications, prepared as a third-person biographical summary:

Ron Graves joined Oak Ridge National Laboratory in 1976 after receiving his PhD in Mechanical Engineering from the University of Tennessee. As a graduate student he conducted research on the use of anhydrous ammonia as an engine fuel, ultimately including experiments in a vehicle in a student competition. He is presently a member of the Engineering Science and Technology Division, and is the Director of the Fuels, Engines, and Emissions Research Center (FEERC) with programmatic, technical, and strategic responsibility for this Department of Energy (DOE) User Facility and the numerous projects conducted therein. Ron was national project manager for the DOE Alternative Fuels Utilization Program from 1984-1990. He continues in a prominent role in that as well as other DOE fuels and engines programs. In 1997 he was chosen by DOE as the technical coordinator for the Diesel Crosscut Team and continues in that role. He was a member of the DOE/Industry Advanced Petroleum Based Fuels (APBF) Steering Committee, the DOE program that contributed heavily to the EPA rule for lowering sulfur in diesel fuel in December 2000. He led the emission control subteam for the 21st Century Truck Technical Roadmap. In 2002, he was appointed as ORNL's representative to the DOE 21st Century Truck Partnership "Lab Council" to facilitate government-industry interactions in that initiative. He is an invited member of the FreedomCAR Advanced Combustion & Emission Control Tech Team. Ron has a record of approximately 55 publications and reports that encompass subjects in fossil energy, internal combustion engines, fuels, and materials. He has been invited to deliver tutorial presentations in major technical conferences as well as informative talks to non-technical audiences. He is a Fellow of the Society of Automotive Engineers and has organized or chaired over twenty technical sessions at technical conferences. He has three patents, with one additional in progress. He is a licensed Professional Engineer in the State of Tennessee.

As requested in the transmittal letter, I hereby affirm that I have no real or perceived conflict of interest as a reviewer of the subject report. I am pleased to have been given the opportunity to review this report and make a modest contribution to EPA's rulemaking process. Please feel free to contact me for clarifications on any of the review comments.

Sincerely,

Ronald Graves, PhD
Center Director
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2360 Cherahala Blvd
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Enclosure:
Review comments on *A Study of the Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies*, dated November 9, 2007

Review Comments on
A Study of Potential Effectiveness of
Carbon Dioxide Reducing Vehicle Technologies
November 9, 2007 Draft

Submitted by
Ron Graves
Oak Ridge National Laboratory
November 18, 2007

Clarity and Understandability (this section of review comments also includes minor editing, grammar, word-processing issues)

Many comments and questions that came to mind while reviewing this report could be covered in a Preface added to this report, written by EPA. Why no hybrids in the study? What justification for aero and rolling drag factors? Why the UDDS instead of LA92 cycles?

In the Executive Summary inform reader straightaway that CO2 and more customary measure of mpg are related merely a conversion factor based on fuel properties. Figure 1-1.

Section 1.3. *Technology* misspelled

Table 1-1 Start off without using so many acronyms. Improving this may be as simple as using smaller font in table to allow more complete wording. If acronyms essential, define them up front.

For clarity, define the "combined" mpg and CO2 values and state whether any correction factors were applied.

P13. First line of 2.4. *that* should be *than*

P35. Last paragraph. ….vehicle data *was* attributed…. Should be *were*

The technology descriptions are informative and clear for the most part.

P59 Last line typo ….Tier 2 Bin 5 (T2B5)….

Tables 7-5 through 7-19 presently include the baseline vehicle characteristics. This adds clarity and ease of reading. Recommend including baseline info in Tables 7-1 through 7-4.

Table 7-5. The list of incremental actions does not appear to be consistent with Package Z. Where are CCP, DVVL effects in Table 7-5? Other similar tables appear to be consistent with package descriptions.

To a technical reader, Tables 7-5 through 7-9 are some of the more interesting.

In tables 7-5 through 7-9, how much influence is there from the sequence in which technologies are added. A comment on this would be useful.

Reasonableness of Methodology and Assumptions

Page 3 and in Exec Summary, the mostly-uniformly applied reductions in aero drag and rolling resistance are without supporting data or analysis. Perhaps this is covered in another study, but is conspicuously lacking the rigor of the remainder of the analysis. Aero and rolling loss factors for trucks are different than cars. Why?

In section 7 we see that the 20% aero drag reduction produces incremental benefits as great or greater than most powertrain options, furthering the need to explain the reasonableness of this assumption. At least cite any thorough analysis to establish feasibility.

Section 2.1, the philosophy of maintaining vehicle performance in the analyses is commendable and appropriate. The report would be additionally instructive if the effect of reduced performance on CO2 was shown for some example vehicles.

P 15, Sect 2.8. The reader is left to assume that other powertrains like hybrids are being addressed separately by EPA.

P 30- Start Stop model. Engine shut-off/restart is certainly an effective technology for reducing idling fuel use. The model or strategy appears to hinge on coolant temperature as the principal signal to manage the on-off cycle. Is it well-established that the coolant temperature is indicative of the exhaust catalyst temp that is so crucial for emission controls? I would have thought a catalyst temp monitor would have been desired.

It is apparent that the impact of the cost of the technology options is beyond the scope of this study. Nonetheless, the cost or price will tend to have great impact on implementation of any technology.

Appropriateness of data

See many of comments in previous section.
Although numerous publications are cited for data, much of the input data are held as proprietary and undisclosed. This could give rise to the results of the study being challenged. Ricardo has an excellent international reputation, but will it be sufficient to deflect doubts as to accuracy of input data and assumptions. An alternate would be to use more data from the public domain.

P40. It would be useful to see the bsfc data that show the impact of cam phasers, said to be widely used. Hence the data should be relatively non-sensitive. Similarly, the valve control options are seen later as having major impact on fuel efficiency. The lack of supporting data in the report leaves the reader questioning the results.

P.50-51. Boosted downsized engines might be expected to have less weight. The report does not address this. Does the vehicle simulation account for weight differences of any of the powertrains? The boosted-downsized engine would appear to have the greatest weight reduction potential.

P54. Outlook for HCCI. We are likely to see some partial use of HCCI modes within 5 years.

P59. Diesel. The system shown in Fig 5-19 is only high-pressure (HP) loop EGR. A better balance between in-cylinder emissions and aftertreatment required may be achieved with HP plus low-pressure loop EGR. EGR loop catalysts may not be adequately effective to prevent fouling.

P60. Did the engine-out NOx map include much operation in PCCI modes? What fraction of operating range? The 60-75% LNT reduction may be a bit high for a very effective PCCI engine.

P62. The 550C regeneration temperature for DPF is rather high if a catalyzed device is used. Balance point temps are more like 350C. Would this lower the fuel penalty in the simulation?

In general there seems to be inadequate attention or discussion about weight differences among the technology packages. Are we to assume that all engine and transmission options had same weights? At least there should be some discussion of this.

Table 7-9. We have seen diesel applications in prototype light trucks getting 35-50% higher "tank mileage" than SI with similar performance (published). 20% gain seems very conservative. With good PCCI systems, we should see aftertreatment penalties closer to 3%. Consider including a simple explanation why 20% is the correct value in view of more optimistic published reports.

Recommendations for Alternate Methods

See comments in previous section.
Show examples to indicate degree of sensitivity to drive cycle for representative technology package (LA92, for example, vs UDDS).

The report would be additionally instructive if the effect of reduced performance on CO_2 emissions was shown for some example vehicles.

The report overall deserves high praise for its breadth and thoroughness, especially considering the accelerated schedule for performing the simulations and writing the document.