Peer Review of FEV Inc. Report "Light Duty Technology Cost Analysis, Power-Split and P2 Hybrid Electric Vehicle Case Studies"

United States
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Peer Review of FEV Inc. Report "Light Duty Technology Cost Analysis, Power-Split and P2 Hybrid Electric Vehicle Case Studies"

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

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1. Introduction

The U.S. Environmental Protection Agency's (EPA's) Office of Transportation and Air Quality (OTAQ) is developing programs to control greenhouse gas (GHG) emissions from light-duty highway vehicles, which require an evaluation of the costs of technologies likely to be used to meet any standards. EPA contracted with FEV Incorporated to perform this cost analysis through tearing down vehicles, engines, and components, both with and without these technologies, and evaluating, part by part, the observed differences in size, weight, materials, machining steps and other cost-affecting parameters. Though complex and time-consuming, EPA believes this approach has great potential for determining accurate technology costs, a goal that is of paramount importance in the setting of appropriate GHG standards.

Although the teardown and analysis work is ongoing, FEV wrote a report detailing the methodology it and its subcontractor are using to cost out technologies and describing the results of the cost-out work to date.[1] To assure that this work incorporates the highest quality science, EPA contracted with ICF International (ICF) to determine appropriate independent peer reviewers for the FEV report, "Light Duty Technology Cost Analysis, Power-Split and P2 Hybrid Electric Vehicle (HEV) Case Studies" and document their feedback on the costing methodology it presents. The reviewers selected were independent subject matter experts and their reviews were conducted in compliance with EPA peer review guidelines.[2]

This report presents the findings of the reviews conducted by four subcontracted subject matter experts. The peer reviewers were:

1. Mr. Ted Bohn, Argonne National Laboratories
2. Dr. Linos Jacovides, Delphi (Retired)
3. Ms. Linda Miller, independent consultant
4. Dr. Deepa Ramaswamy, Hybrid Chakra

2. The Peer Review Process

From December 2010 to April 2011, EPA contracted with ICF to coordinate this peer review. ICF implemented the peer review in compliance with EPA's *Peer Review Handbook* (3rd Edition).[2] EPA requested that the peer reviewers represent subject matter expertise in manufacturing cost estimating and/or automotive design.

ICF developed a list of candidate peer reviewers from the following sources: (1) ICF experts in this field with knowledge of relevant professional society membership, industry, academia, and other organizations, and (2) suggestions from EPA staff. ICF identified 25 qualified individuals as candidates to participate in the peer review. ICF sent each of these individuals an introductory screening email to describe the needs of the peer review and to gauge the candidate's interest and availability. ICF attached to the email the reviewer charge to ensure each candidate was familiar with the scope of work. ICF also

[1] Draft Report FEV07-069-303F, February 22, 2011.

[2] EPA's Science Policy Council. *Peer Review Handbook*, 3rd Edition (http://www.epa.gov/peerreview/).OMB's Information Quality Bulletin for Peer Review and Preamble (also in the EPA's Peer Review Handbook, Appendix B).

asked candidates to provide an updated resume or *curriculum vitae* (CV). Several candidate reviewers were unable to participate in the peer review due to previous commitments, and several others did not respond. ICF reviewed the responses and evaluated the resumes/CVs of the interested and available individuals for relevant experience and demonstrated expertise in the above areas, as demonstrated by educational degrees attained, research and work experience, publications, awards, and participation in relevant professional societies.

ICF reviewed the interested, available, and qualified candidates with the following concerns in mind. As stated in the EPA's *Peer Review Handbook*, the group of selected peer reviewers should be "sufficiently broad and diverse to fairly represent the relevant scientific and technical perspectives and fields of knowledge; they should represent a balanced range of technically legitimate points of view." As such, ICF selected peer reviewers to provide a complimentary balance of expertise of the above criteria.

EPA reviewed ICF's proposed peer reviewers and concurred with ICF's recommendations; these peer reviewers were listed in the introduction. **Exhibit 1** shows the representation of the peer reviewers in the required areas of expertise.

Exhibit 1. Chart of Peer Reviewer Expertise Areas and Affiliation

Expertise Areas/ Affiliation	T. Bohn, Argonne National Laboratories	L. Jacovides, Delphi (Retired)	L. Miller, independent consultant	D. Ramaswamy, Hybrid Chakra
HEVs	✓	✓	✓	✓
Cost Modeling	✓			
Manufacturing		✓	✓	✓
Mass Production		✓	✓	✓
Tier 1 Supplier				✓
Original Equipment Manufacturer (OEM)		✓	✓	✓

Prior to distributing the review materials, ICF sent each of the reviewers a conflict of interest (COI) disclosure and certification form to confirm that no real or potential conflicts of interests existed. The disclosure form addressed topics such as relationships with the report's authoring organization, employment, investment interests and assets, property interests, research funding, and various other relevant issues. Upon review of each form, ICF determined that each peer reviewer had no COI issues. ICF executed subcontract agreements with all of the reviewers.

ICF provided peer reviewers with the following materials:

- Draft report by FEV, Inc., entitled, "Light-Duty Technology Cost Analysis Power-split and P2 HEV Case Studies," dated February 22, 2011;
- The Peer Reviewer Charge to guide their evaluation; and
- A template for the comments organized around the Peer Reviewer charge.

The Peer Reviewer Charge provided peer reviewers with general guidelines, as well as example questions, for preparing their overall review, with particular emphasis on methodologies and cost results. In addition, EPA asked each reviewer to provide recommendations on the "overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model."

A mid-review teleconference was held on March 8, 2011, to discuss the charge, the purpose of the review, and to answer any outstanding questions the reviewers might have. The call was moderated by ICF and attended by reviewers Mr. Bohn, Dr. Jacovides, Ms. Miller, and Dr. Ramaswamy, as well as EPA staff Brian Nelson, and FEV, Inc. staff Greg Kolwich who were familiar with the report.

The charge to peer reviewers is provided in **Appendix A**. The CVs or resumes for the reviewers are included in **Appendix B**.

3. Summary of Peer Reviewer Comments

This section presents a brief summary of the various comments received from the peer reviewers. The intention here is to convey the overall results of the individual peer reviews in a concise summary highlighting any lessons learned.

This summary is organized into two categories, issues related to study methodology and results and general observations of the study. Editorial comments were excluded from this summary and may be found in the full verbatim comments that are provided in Section 4.

3.1. Comments on Methodology/Results

a. Reasonableness and Potential Bias of the Methodology as Documented

Dr. Jacovides stated that the methodology is correct and can lead to correct results, as he had familiarity with the approach and expected results from prior work. Given that familiarity, he felt the report represented a superb implementation of the concept and that the analysis of the HEV and internal combustion engine (ICE) equivalent was done very carefully, correctly, without any obvious bias, and achieved results in agreement with his own. Mr. Bohn agreed generally, but only for the baseline HEV.

However, two other reviewers expressed skepticism. Ms. Miller felt that the methodologies are generally reasonable, but raised some specific concerns, including a lack of documentation proving accurate results. Specifically, she noted that, while the paper references marketplace validation, no examples were given. Dr. Ramaswamy agreed that the report does not sufficiently document the validation of the methodology at a subsystem or a system level. The implication was that, while the bottom-up approach was highly detailed, insufficient data was given in the report to show that the resulting subsystem or system costs agreed with those developed or published by other reasonable sources. Ms. Miller also noted that the methodology only predicts absolute costs, and that a sensitivity analysis should be included and documented. Dr. Ramaswamy agreed that the methodology for determining costs is generally reasonable, but highlights some significant exceptions. Specifically, engineering development costs and use of indirect cost multipliers (ICMs) was not considered in sufficient detail and may be incorrect. An example was given (see specific comment excerpt number 8 in Table 1) where ICM costs are incorrectly applied to the OEMs. This would introduce bias to lower predicted costs beyond reality, thus the engineering development costs for the subsystems should be revised. Ms. Miller also noted that the scaling methodology appeared to be overly simplified when it was applied to labor and manufacturing overhead. Whereas the cost of direct labor is more a factor of part complexity than one of size, certain elements of overhead costs were only minimally affected by part size. This could introduce bias that should be explored through use of sensitivity tests.

The only key limitation Dr. Jacovides noted is that the methodology was limited to the two architectures studied (split power hybrids used by Toyota and Ford and, to a limited extent, Hyundai's P2 architecture). While he noted that the P2 battery was properly analyzed by tear down of an actual unit and could be extended to other hybrids (GM [two mode and the Malibu ISG] and the Honda Insight), Mr. Bohn expressed skepticism about the general subjectivity of the scaling assumptions, particularly for P2 HEVs, but, while noting that bias was possible, he made no judgment on its direction or magnitude. However, a general consensus seemed to be that the P2 HEV results were more likely to be erroneous than the scaling to other vehicle types, which was, in turn, likely to be more erroneous than the results for the baseline vehicles.

b. General Flaws in the Scope of the Study

Mr. Bohn suggested that the scope is "just right" and offered no conclusive statements. He noted that expanding the scope of the study would likely introduce more variability and that reducing it would not necessarily increase its validity or accuracy.

Dr. Jacovides said that, although beyond the scope of this report, the study results would be meaningless without knowledge of appropriate use of ICMs. This was a limitation of the study—the study may be sufficiently detailed exclusive of ICMs, but end results could vary by up to a factor of two depending on the ICMs.

As introduced previously, more substantial concerns were raised over the scaling of results, especially to P2 HEVs. Dr. Jacovides expanded on the comments from part (a), expressed concerns about both the methods and results for the P2 system. While the results of scaling for the P2 system may be in the right direction, the sizing of the electrical system (power electronics and the electrical machine) were likely incorrect. Because the duty cycle of the electrical system in a P2 HEV is very different than that of the power split HEV, the ratios of copper to iron in magnets will likely be different. Further, if the electrical machine for the P2 was sized based on power, this was incorrect. Instead, torque and duty cycle are the primary determinants of size (and cost). Also P2 HEVs have a clutch to disconnect the engine so that regenerative braking does not have to be reduced to provide for engine friction thus providing an all electric range (AER). The resulting 32.4kW power of the electrical machine will not provide sufficient required torque and power for AER. Further, since the size of electrical machine is determined by torque, not power, a slower speed machine will be heavier which contradicts the assumed 20% vehicle curb weight reduction for the P2 architecture for all vehicle segments. Dr. Ramaswamy agreed that the assumption of a 20% power and weight reduction assumed for the P2 hybrid may be unjustified. Further, she found that there is no justification in other literature that the Lithium Polymer battery (as opposed to nickel metal hydride [NiMH]) would be a better long term solution for the P2 hybrid.

Dr. Jacovides argued that the study will be difficult to apply to other vehicles or architectures without the detail provided by a similar tear-down. Ms. Miller agreed that extrapolation to other vehicle sizes cannot be done without the basic underlying detailed studies, and that extrapolation of costs for vehicles other than the Fusion relies on use of scaling and does not have the same level of detail as the rest of the study. A different use of scaling factors, such as by applying scaling factors to material cost and investment in equipment instead of for manufacturing cost and burden could yield a very different result.

The general consensus was that the scaling portion of the study was the most dubious.

c. Appropriateness of Study Inputs

Dr. Jacovides reiterated his contention that the report's central analysis (comparison of a hybrid and an ICE Fusion) was very well done. However, he raised concerns with estimation of the following cost assumptions: 1) development of control software, 2) integration of the electrical and mechanical parts, and 3) calibration. All are upfront engineering costs that should be considered as part of the cost of the vehicle, although they may be insignificant by the time production volume has reached 450,000 units.

Ms. Miller was concerned that lack of communication with the OEM's – while consistent with EPA policy – can lead to inappropriate validation of the teardown costing. Dr. Ramaswamy agreed that insufficient independently determined system/subsystem costs were used to validate the calculated costs. The report does discuss this, but specific examples of validation should be considered as additional inputs to the process.

Dr. Ramaswamy also argued that the major flawed assumption of this study was that the high voltage battery will be manufactured in the United States. NiMH batteries are not manufactured in volume in the United States. Although several companies have plans to manufacture Li-ion batteries, the cells typically come from Asia. This inaccurate assumption biased the cost results high.

d. Reasonableness of Assumptions

Reviewers noted concern about several assumptions included in the study. Dr. Jacovides again noted his general conclusion that while the assumptions used are appropriate, the implicit assumption that a downstream user without the same expertise as FEV would be able to run the model is unlikely. Dr. Ramaswamy agreed that assumptions were generally reasonable, but highlighted especially the unreasonable assumption incorporated in the scaling parameter for the battery.

Ms. Miller listed the following specific assumptions that should be re-considered:

- The assumption that the technologies used may be considered mature should be evaluated. The assumption of maturity impacted numerous underlying cost elements, including lack of allowances for learning, scrap rates, non-recovered engineering, design, and testing (ED&T) expense and capital costs, and equipment end of life costs.

- The assumption that no new or modified equipment maintenance is required is inconsistent with equipment at the end of its life cycle, assumed above. Together, these biased the cost estimates low.
- The assumption that integration of new technology would be planned and phased in to minimize non-recoverable expenses would be cost effective. In reality, new technology requirements to achieve fuel economy improvements and emissions reductions will preempt this consideration.
- The markup rate needs to vary dependent upon the part size and part complexity. If tolerance limits are not considered part of part complexity, tolerances need to be considered as another factor in determining scrap rates. Assumed scrap rates should also be verified.
- The assumption that all sourcing/manufacturing centers will be in the United States was not valid and could bias the results high or low.
- Assumed labor rates may need to be adjusted to include overtime costs and other premiums. It was unclear from the report if this was included and could bias the results, depending on union agreements and/or operating practices.
- Packaging cost assumptions should be checked, based on the sample calculation (page 50, Figure C-6).
- Allowances for a percentage of pallets/racks out for cleaning/repair are not included and biased the packaging cost low.
- The assumed Cost of Complexity is inappropriate. Volumes of 450,000 per year assumed that the major complex assemblies (engine, transmission, and complex subsystems) are produced on dedicated lines. If they are not, then a cost of complexity factor needs to be added. The 75% combined utilization/efficiency assumption was reasonable unless hybrid components are assembled on the same lines as the baseline products (as they will be), in which case this utilization/efficiency is over-stated. This biases the results low; additional complexity should be factored into the utilization/efficiency calculation.
- With respect to System Scaling Cost Analysis, ratios used to develop sizes and material costs for HEV components (traction motors, high traction batteries, etc.) were appropriate, but use of these ratios to determine other factors (especially labor and P2 HEV powertrain components) was less valid. These are more related to part complexity than part size. Which costs are scalable should be reevaluated.

Mr. Bohn discussed some assumptions, particularly regarding the base vehicle and the P2 Hybrid having equivalent performance with increased fuel economy. He said associated assumptions about the amount of engine blending and depth of battery discharge were subjective and expressed concerns regarding the lack of electric machine rating standards. However, he made no mention of their reasonableness or direction of influence on the study’s results.

e. Appropriateness of Results

Three of four reviewers generally considered the study results appropriate but commented on the need for increased validation. Dr. Jacovides commented that the results were reasonable, but noted that it would be useful to have Ford and Toyota review them before making the report public. Dr. Ramaswamy agreed that the results were appropriate for the given scope, assumptions, and inputs, but noted that the description of the validation of the costing methodology was insufficient and that a sensitivity analyses and further analyses/correction of some assumptions were warranted. Mr. Bohn, too, agreed that the results were reasonable given the scope, assumptions, and inputs, but felt that reasonable validation was achieved, although he considers the level of validation appropriate to be subjective.

Ms. Miller disagreed. She felt that, given the levels of assumptions made, at best cost estimates are directionally correct, which is inconsistent with the stated goal of absolute costs. In particular, she had concerns regarding validation. While the methods used were solid (teardown analysis, process flow diagrams, analysis of comparable parts, etc.), numerous methodological assumptions were used and their validation is insufficiently documented. She recommended sensitivity testing, appropriate and correct accounting for component sourcing, and reevaluating labor costs.

f. Appropriateness of Scaling Costs to Other Vehicle Classes and to Other Hybrid Technologies

Generally reviewers seemed to express more reservation about the scaled results than the baseline vehicles, for a variety of reasons.

Dr. Jacovides noted that scaling for vehicles with identical architecture but different power inappropriately account for labor. Similarly for P2 HEVs, costs for electrical machines should not be scaled as power, but on torque and duty cycle. Ms. Miller agreed that the ratios used to size HEV components was appropriate for material costs and investment in equipment, but that using the size ratio scaling methodology for overhead cost, direct labor costs, and required staffing was inappropriate. She had these same concerns with scaling for the P2 HEV calculations. Dr. Ramaswamy also agreed that for most components, the scaling to other vehicle classes was reasonable. Mr. Bohn added that while the approach used in scaling appears reasonable, he had concerns that the actual values used in the scaling approach could be off and lead to erroneous results. However, this was not supported by his general conclusion above regarding the reasonableness of results.

Mr. Bohn and Dr. Jacovides commented that the NiMH battery scaling was done correctly, although Dr. Jacovides noted that scaling did not consider an alternative approach of using a larger number of smaller cells. He believed that the approach used for the P2 architecture was directionally correct but the results would not be as accurate as those between the baseline hybrid and ICE vehicles. Although he noted that the estimated cost of the cells seemed reasonable, Dr. Jacovides raised two questions about the treatment of the Li-ion battery: 1) that discussion should be added to explain preservation of battery life when scaling by nominal kWh, and 2) that clarification should be made on what size battery is cost for the P2 HEV. Dr. Ramaswamy agreed. She noted that scaling of parameters across different vehicle classes needed to be better explained and justified, given that this one component was responsible for the bulk of the cost of the hybrid powertrain.

3.2. Comments on Other/General Observations

General comments not included in the earlier sections are discussed in this section.

Ms. Miller complemented the detail and effort of the analysis and report and the use of recognized methodologies. Dr. Ramaswamy noted a small number of omissions and discrepancies. She noted that, while the report talked about the applicability of the power split hybrid system to the sub-compact, small, large, and minivan vehicle segments, it should clarify that this group also covers small SUVs such as the Ford Hybrid Escape, which is one platform that already supports this architecture.

Dr. Ramaswamy also noted several specific items of concern. She indicated that the study seemed to omit a high-voltage DC/DC converter used by the traction motor and generator, which is used in the Fusion Hybrid and should be included in the cost. Table E-2, compared to those in Table D-3, showed inconsistencies that should be addressed. Dr. Ramaswamy also noted that Table A-1 should have calculated the percentage increase as compared to the base non-hybrid vehicle cost, instead of calculating the increase with respect to the mid/large size vehicle segment cost. Also, in Figure B-1, she questioned why the bill of materials (BOM) was not updated after step 6, when additional information has been gained about the component after its disassembly. She also asked what the 19,149 parts stand for on page 50, first paragraph.

Dr. Ramaswamy also believed the methods for determining the engineering design costs for various components/systems were unclear. These included: 1) the Atkinson engine engineering design cost, associated control system, and calibration; 2) the engineering design cost for the electronics controllers, software for the battery system, and mechanical design of the battery system (the numbers presented appear low); 3) the ED&T for the traction battery assembly (too high relative to that for the control module, given the relative engineering efforts) (Table D-11).

Dr. Jacovides recommended specific companies that should be consulted to assess the accuracy of results: Ford for the baseline vehicles and those scaled according to size and Honda or GM for scaling to P2 HEVs. Also, individual component costs should be compared to those used on the Volt and Leaf.

Ms. Miller also noted that validity testing of the Munro & Associates software, FEV databases, and costing algorithms should be performed and documented. Hypothesis testing of assumptions concerning burden rates, product maturity, etc. and sensitivity analysis to demonstrate correlation to actual component costs should also be added to the study.

4. Verbatim Peer Reviewer Comments in Response to Charge Questions

Table 1 presents the verbatim comments received by the three subject matter experts. Comments are sorted by charge question and then topic/categories. **Appendix C** provides the actual peer reviewer comments.

Table 1. Sorted, Verbatim Comments from Reviewers

Charge Question Topic	Specific Assumption/ Topic	Com-ment Excerpt No.	Reviewer	Comment Excerpt
Methodology/ Results	Methodological Issues	1	Bohn	Overall, the draft document presents a generally reasonable methodology that is likely to yield accurate results.
Methodology/ Results	Methodological Issues	2	Bohn	The assumptions used for the P2 HEV system are somewhat subjective on adding the P2 functionality as an 80/20 power sharing between engine and motor for peak conditions. This may introduce a bias in the results of the benefit vs the component cost, or in this case incremental costs. The assumption about engine downsizing is that the base vehicle and the P2 Hybrid will have equivalent performance with increased fuel economy. While peak performance is straight forward to assess for both the baseline and P2 Hybrid versions, the amount of engine blending, depth of discharge of the batteries, etc will affect the assessed fuel economy.
Methodology/ Results	Methodological Issues	3	Bohn	It is difficult to assess the direction of the bias (cost or performance/F.E. mismatch)- i.e. component sizing is cost sensitive and depending on the engine/motor torque blending, component cost may be over stated or understated based on blending assumptions and equivalence the to the base vehicle.
Methodology /Results	Methodological Issues	4	Bohn	There is no simple remedy for this supposed bias since engine downsizing and component sizing are subjective based on the desired performance attributes to compare the hybrid version to the base vehicle. The assumptions made in the report (section A) are fair, and clearly stated.
Methodology/ Results	Methodological Issues	5	Bohn	As with many vehicle simulations, the component scaling methodologies need validation. In some industries, component scaling is limited to technology or performance ranges. For instance IGBT transistors versus MOSFET transistors are used for two different voltage ranges with some overlap. Even so, the scaling assumptions are bounded by the available voltage limit for the transistors. Scaling up power ratings on an inverter, or battery voltage have impacts on the scaled inverter costs, caused by (for instance) the boundary where one would use MOSFETs for lower voltage and IGBTs for high voltage.
Methodology/ Results	Methodological Issues	6	Jacovides	The methodology is clearly correct and could lead to correct results. As stated above, I am familiar with the approach because it was discussed during the NRC committee on "Improving the Fuel Economy of LDV" and in the references listed earlier. The report, under review, represents a superb implementation of the concept.

Methodology/ Results	Methodological Issues	7	Jacovides	The analysis of the Ford Hybrid and cost comparisons with its ICE equivalent is done very carefully and correctly without any bias that I can detect. Interestingly the increase in cost of $3435 that this report comes up with is almost identical to the one we came up for the Prius in the NRC study of $3385. We did that by talking to OEM's and suppliers. However I want to emphasize that the approach taken by this report is far superior. As long as a detailed design or an actual vehicle is available this is the way to do it. It does require a great deal of industrial engineering skill to estimate the amount of labor, and cost of materials but in the hands of FEV this has produced excellent results
Methodology/ Results	Methodological Issues	8	Jacovides	It should be pointed out that the methodology is limited to the two architectures studied viz. split power hybrids as implemented by Toyota and Ford and to a limited extend on the P2 architecture as implemented by Hyundai. I say limited since there was no design available for the electrical machine in this case. The battery for the P2 was properly analyzed by tear down of an actual unit. Nevertheless the analysis can be extended to other hybrids such as the two types made by GM (two mode and the Malibu ISG) and the Honda Insight
Methodology/ Results	Methodological Issues	9	Miller	• While the methodologies, for the most part, appear reasonable, there are some areas of concern. There is a lack of documentation in the paper proving that the methodologies yield accurate results. While the paper references marketplace validation, no examples are given. • Recommendation: Include examples taking developed costs for items such as fuel injector assemblies(Figure C-3, page 45, Sample MAQS Costing Worksheet); extrapolating these to a total cost using the approach outlined in the paper; and then comparing these costs to actual marketplace pricing for the example used. One or two worked examples of this nature would help to validate the overall methodology. Alternatively, include a table, detailed by component/ sub-assembly, showing the methodologies and comparisons used for costing each item.
Methodology/ Results	Methodological Issues	10	Miller	• The costing methodology, as presented, develops costs that are absolute. Given the complex nature of the end product and the manufacturing processes, it would have been appropriate to include sensitivity analysis in the costing detail. If sensitivity analysis has been performed on a sampling of costs, it is not shown in the paper. • Recommendation: Assuming sensitivity analysis is available, show the impact of sensitivity analysis in the examples in the paper. If sensitivity analysis has not been performed, then this is an area of detail that needs to be completed. From a manufacturing perspective, sensitivity analysis on high dollar components needs to include scrap rates, mean time to repair of equipment, equipment uptime, etc.

Methodology/ Results	Methodological Issues	11	Miller	The scaling methodology appears to be overly simplified. For example, scaling factors are applied to labor and manufacturing overhead. The cost of direct labor is more a factor of part complexity than one of size. Also, certain elements of overhead cost such as salaries and front office costs are not impacted, or at most minimally, by part size. •Recommendation: A deeper review of the approach to scaling needs to be undertaken to insure that costs are not under/over-stated. Again, applying sensitivity tests may help determine whether or not these differences are significant.
Methodology/ Results	Methodological Issues	12	Miller	Without the documentation noted above, it is not possible to say whether or not bias has been created.
Methodology/ Results	Methodological Issues	13	Ramaswamy	The methodology for determining the costs are generally reasonable, with some significant exceptions that are listed below. • The first is the engineering development cost, which appears to have been not considered in detail in this report. An example of these are the costs to develop control systems, be they battery control systems or otherwise. They cannot be lumped in with the indirect cost multipliers (ICMs), because these costs are not borne by the OEMs. Rather, these are costs borne by the suppliers. The bias introduced by this is that the overall cost of some components is lower than it should be. The remedy for this is to revisit the engineering development costs for the subsystems.
Methodology/ Results	Methodological Issues	14	Ramaswamy	What this report does not document sufficiently is the validation of this methodology at a subsystem or a system level. The bottoms up towards cost that is employed by FEV is certainly very detail oriented, but there isn't sufficient data in the report to show that the final subsystem or system costs that they result in, are inline with those developed or published by other reasonable sources
Methodology/ Results	General Flaws	15	Bohn	The scope of the document is broad reaching. Expanding the scope of the study would likely introduce more variability with increased assumption.
Methodology/ Results	General Flaws	16	Bohn	The scope does not need to be reduced since it covers many aspects on the cost of producing an automobile and reducing the scope would not necessarily increase the validity or accuracy of the study.
Methodology/ Results	General Flaws	17	Jacovides	The results of this study cannot properly be evaluated without knowledge of what EPA considers the IC factor to be. I realize that this is not in the scope of the report. However IC factors range from 1.02 to 1.45 as stated in reference 5. Industry RPE factors were estimated in Reference 4 to be 1.5 or 2.0 depending on whether parts were bought or made in house. One can calculate manufacturing costs to the penny but then the end result can vary by a factor of up to two depending on the multiplier

Methodology/ Results	General Flaws	18	Jacovides	The results for the P2 may be directionally correct, but I am concerned about the sizing of the power electronics and the electrical machine. FEV should have bought a Honda Insight (IMA), available in the US in the spring of 2010, or a GM Malibu (ISG) for a tear down of the electrical system (Power electronics and machine). The duty cycle of the electrical system is very different than that of the power split and so the ratios of copper to iron to magnets will likely be different. Also it seems from Table F2 that the electrical machine was sized based on power. As discussed below torque and duty cycle are the primary determinants of size and hence cost. It should be pointed out that P2 has a clutch which provides two features that the Insight and the Malibu do not have. The clutch can disconnect the engine so that regenerative braking does not have to be reduced to provide for engine friction and can provide an all electric range (AER). The 32.4kW power of the electrical machine will not provide the required torque and power. There should be a statement to the effect that the P2 is not designed to provide an AER
Methodology/ Results	General Flaws	19	Jacovides	Another problem is the assumption of a 20% vehicle curb weight reduction for the P2 architecture and for all vehicle segments. Such a reduction does not come for free and I found no rationale for this. In reference 4 we found that a 10% reduction in a 3600 lbs vehicle would add around $700. During the conference call it was implied that the P2 electrical systems is lighter. This may not be so and certainly not by 20%. The speed of the P2 electrical machine is not an independent variable and it is much lower than the speeds of the two power split machines. The size of electrical machines is determined by torque and not power and so a slower speed machine will be heavier. Clearly getting an Insight or a Malibu would have given a better estimate.
Methodology/ Results	General Flaws	20	Jacovides	Another flaw of the study is that it depends on the ability of the people using the study to turn the crank for other vehicles or for vehicles without the detail provided by a teardown. Clearly FEV has demonstrated that it is developing that knowledge, although I am not sure about the accuracy of the electrical systems numbers for the P2. The question then becomes “will EPA need FEV in the future in order to use this work”. Based on the conference call with EPA, FEV and the Reviewers, this study will not be used for other architectures so the above point is moot. However I would like to caution that any extension to other architectures needs to be done by skilled manufacturing engineers and cost analysts.

Methodology/ Results	General Flaws	21	Miller	• I do not see any general flaws inherent in the scope of the study. Extrapolation to other vehicle sizes could not be done without the basic underlying detailed studies. However, once the component costs had been developed for the Fusion, the justification for the extensive use of scaling factors to approximate these costs for other vehicle lines does not have the same level of detail as the rest of the study. Whether or not this has been impacted by the scope of the project can not be determined. • Recommendation: Review the application of scaling factors, especially for manufacturing cost and burden. The methodology described in the paper yields a result that should be considered as one end of a range estimate. The other end of the estimate should be developed by applying scaling factors to material cost and investment in equipment and holding the other costs constant. If it is necessary to state an absolute cost, the pick a middle ground between these two numbers based on expert opinion.
Methodology/ Results	General Flaws	22	Ramaswamy	Although not a flaw per se, it is not clear why the 20% power and weight reduction was assumed for the P2 hybrid. This was the direction provided by the EPA to FEV, but the rationale for this is not clear, and this reviewer could not see why it is justified.
Methodology/ Results	General Flaws	23	Ramaswamy	Secondly, the reports stated that the team felt that the Li Polymer battery (as opposed to NiMH) is a better long term solution for the P2 hybrid. It's unclear if this was the EPA team or the FEV team. Either way, there is no good rationale provided for such a statement, and this reviewer has not seen data (even outside of this report) to justify such a statement.
Methodology/ Results	Appropriate Inputs	24	Bohn	The scope and breadth of inputs used for the study and cost assessments are broad and apparently all encompassing. There are many input items on costs, such as labor rates and overhead on labor, which are outside the expertise of this reviewer. To the best of my knowledge, all the inputs used in this study are appropriate.

Methodology/ Results	Appropriate Inputs	25	Jacovides	When it comes to the main part of the report i.e. the comparison between a hybrid and an ICE Fusion everything seems to be done very well. Possible exceptions are in estimating the following costs 1.Development of control software. 2.Integration of the electrical and mechanical parts. 3.Calibration. Hybrid vehicles are more complex and to make performance transparent to the driver is expensive. Safety also requires extensive calibration. Toyota has recalled the 2010 Prius to fix software when braking on ice on bumpy roads. If this can happen to Toyota with 10 years experience on hybrids, it must be taken seriously. These are upfront engineering costs and by the time production volume has reached 450k units may not be significant. However they need to be added to the cost of the vehicle.
Methodology/ Results	Appropriate Inputs	26	Miller	Although, as explained in the conference call on March 8, 2011, it is EPA policy to perform studies of this nature independent of the OEM's, it would have seemed appropriate to seek validation of the teardown costing from the manufacturer whose vehicle is the basis for this analysis. For a review of other assumptions that are of concern, see the response to the next Question.
Methodology/ Results	Appropriate Inputs	27	Ramaswamy	One of the major assumptions in this study that is flawed is that the high voltage battery will be manufactured in the United States. NiMH batteries are not manufactured in volume in the United States, and although several companies have plans to manufacture Li Ion batteries, the cells typically come from Asia. To assume that all this manufacturing is done in the US will results in artificially high unit costs for these systems. If this information is then used by the EPA for downstream rule making, it will have the effect of having hybrid technologies show up in an unfavorable light as compared to other technologies. This inaccuracy could be remedied by a modification of the assumptions in terms of where the battery will be manufactured.
Methodology/ Results	Appropriate Inputs	28	Ramaswamy	This study does not present sufficient examples of independently determined system/subsystem costs to be used for validation of the costs that FEV/Munro calculates through their process. Although the report mentions this was done (section C.7), examples of such validation are not presented. These independently determined costs/sources should be additional inputs to this process.
Methodology/ Results	Assumptions in Model	29	Bohn	Comments in the boxes above discuss some of the bounded areas of assumptions that affect cost and/or performance, such as engine/motor blending.

Methodology/ Results	Assumptions in Model	30	Bohn	A somewhat contentious point related to assumptions is the component rating system for electric machines. There is currently no published standard for electric machine rating methods in automotive applications. Peak ratings versus average versus steady state, as well as inlet cooling rates and losses at different operating points are tied up in the assumptions used to compare one electric machine to another after the scaling algorithm.
Methodology/ Results	Assumptions in Model	31	Bohn	The model is very comprehensive, and according to the reviewer's teleconference, the authors of this study validated many of the models and component scaling models.
Methodology/ Results	Assumptions in Model	32	Bohn	To the best of this reviewer's knowledge, the assumptions used in this study are reasonable. Inputs on materials cost for the study appear to be reasonable to this reviewer.
Methodology/ Results	Assumptions in Model	33	Jacovides	These seem to me to be appropriate. A problem will arise with the next person who runs the model. Will they have the expertise of FEV, which I think is one of the premier automotive engineering firms?
Methodology/ Results	Assumptions in Model	34	Miller	While the majority of assumptions cited in the study are valid, there are a number of assumptions that need to be re-considered. They are as follows: • The technologies used are considered to be mature. It is more likely that the technology will continue to evolve requiring changes to manufacturing facilities and tooling. The assumption of maturity, for example, impacts a number of underlying cost elements and other assumptions: there are assumed to be no allowances for product/manufacturing learning, scrap rates are minimal, non-recovered E,D&T expense and capital costs are zero, and there are no allowances for equipment end of life costs. All of these stem from the assumption of maturity. At the same time, however, it is assumed that no new or modified equipment maintenance is required (See pages 16 & 17). This is not consistent with equipment at the end of its life cycle. All of the above will cause cost estimates to be understated. • Recommendation: Review the costs impacted by the assumption of maturity. Uplift costs by a percentage factor where appropriate. If the assumption remains that equipment will be at the end of its useful life, then increase maintenance costs over time according to the equipment OEM's guidelines.
Methodology/ Results	Assumptions in Model	35	Miller	• It is assumed that "integration of new technology would be planned and phased in to minimize non-recoverable expenses". This would indeed be the most cost effective decision. However, given the significant requirements for fuel economy improvements and emissions reductions, the need to implement new technology will likely be the over-riding consideration. • Recommendation: Perform cost sensitivity analyses with non-recovered E,D&T and stranded capital in percent increments ranging from 10 to 30 %. Include the results in the paper.

Methodology/ Results	Assumptions in Model	36	Miller	• End-item scrap includes quality defects, rework costs, and/or destructive test parts (page 29). The general mark-up varies from 0.3% to 0.7% depending on part complexity and size (page40, Table C-1). However, it is stated that exceptions are made depending on the part. Examples cited in Section C.4.5.2 include sand and investment casting. These are considered to be "generic" processes and the end-item scrap mark-up is uplifted to 5% in both cases. However, just as in Table C-1, this rate needs to vary dependent upon the part size and part complexity (I am assuming tolerance limits are considered part of part complexity. If not, tolerances need to be considered as another factor in determining scrap rates.) Without a part by part review of the assumptions, the impact to the cost analysis can not be determined. • Recommendation: To test the reasonableness of the scrap percentages, check a random sample of components and compare the end-item scrap rates for those processes to industry standards. Use complexity and size of the parts to adjust averaged rates
Methodology/ Results	Assumptions in Model	37	Miller	• All sourcing/manufacturing centers are assumed to be in the United States. As discussed in the March 8, 2011 conference call, this is not a valid assumption and can significantly impact cost either negatively or positively. • Recommendation: Review present sourcing patterns, at least for the high cost components and sub-assemblies, and utilize these patterns as the basis for the cost analysis.
Methodology/ Results	Assumptions in Model	38	Miller	• Labor Rates MAQS Costing Worksheet Example (page 46). It can not be determined whether or not any overtime costs were assumed in the labor cost/hour calculation. Overtime costs will vary manufacturer to manufacturer based on Union agreements and/or operating practices. However, in a number of cases (Ford Motor Company for one), shifts of 10 hours per day in the United States would generally include 2 hours of overtime pay. Afternoon shift also has an associated premium cost. • Recommendation: Verify underlying assumptions in the labor rate models.
Methodology/ Results	Assumptions in Model	39	Miller	• Packaging Assumptions: Based on the sample calculation (page 50, Figure C-6), allowances for a percentage of pallets/racks out for cleaning and/or repair (generally around 5%) have not been included. This understates the packaging cost. • Recommendation: Increase the # of packaging units required by 5% where returnable packaging is used.

Methodology /Results	Assumptions in Model	40	Miller	• Cost of Complexity Assumptions: Based on the volume assumption of 450K per year, although it is not stated in the report, it is assumed that the major complex assemblies: Engine and Transmission as well as Complex Subsystems are produced on dedicated lines. If not, then a cost of complexity factor needs to be added. The 75% combined utilization/efficiency assumption (calculated based on page 37) is reasonable. However, if hybrid components are assembled on the same lines as the baseline products, then this utilization/efficiency is over-stated due to the inherent inefficiencies caused by manufacturing complexity. Note: It should be assumed that hybrid and base vehicles will be assembled on the same line and so this added complexity must be factored into the utilization/efficiency calculation. • Recommendation: Process flow diagrams for complex base-line vehicle assemblies/components should be compared to those developed for HEV vehicle and adjustments made to the efficiency/utilization percents for HEV based on this comparison.
Methodology/ Results	Assumptions in Model	41	Miller	• System Scaling Cost Analysis: While the use of ratios to develop sizing for HEV components such as traction motors, high traction batteries, etc. is appropriate and can be used to estimate material costs, the use of these ratios to determine other factors within manufacturing cost such as labor (page 126) is less valid. Part complexity influences these costs more than part size. The same concerns exist with establishing component costs for P2 HEV powertrain components using manufacturing cost to component size ratios (page 127). Recommendations: • Re-evaluate the assumptions around use of a scaling factor to better define those costs which are scalable and those which are not. • Assuming the validity of the approach to costing using manufacturing cost to component size ratios, provide background data supporting this assumption. • As outlined above. review the application of scaling factors, especially for manufacturing cost and burden. The methodology described in the paper yields a result that should be considered as one end of a range estimate. The other end of the estimate should be developed by applying scaling factors to material cost and investment in equipment and holding the other costs constant. If it is necessary to state an absolute cost, the pick a middle ground between these two numbers based on expert opinion.
Methodology/ Results	Assumptions in Model	42	Ramaswamy	In general, the assumptions that are utilized to calculate cost and performance are reasonable. One big exception (also mentioned in question 6 below) is the scaling parameter for the battery. Only two paragraphs are devoted to it in the report, and nowhere is a definition of “a common run-time”, which is used in the scaling of the battery, provided.

Methodology/ Results	Result Appropriateness	43	Bohn	Yes. The results expected of the study are reasonable given the scope, assumptions and inputs.
Methodology/ Results	Result Appropriateness	44	Bohn	The net incremental cost for each of the vehicle sizes and two hybrid topologies seems intuitive on cost magnitude, if in fact performance is equivalent.
Methodology/ Results	Result Appropriateness	45	Bohn	This reviewer cannot comment on other results that could be derived from the study.
Methodology/ Results	Result Appropriateness	46	Bohn	Validation is a very subjective process with regard to the 'level of validity'. After reading the study description, and listening to the authors during the reviewer's teleconference where the validation process was described, it appears that reasonable validation was achieved on the costing results.
Methodology/ Results	Result Appropriateness	47	Jacovides	The results are reasonable, not only because the actual number is the same as we got in our study but because the costs are estimated with great detail. I am aware of one other company that has used this approach to come up with detailed costs of automotive components *[Footnote 6: Intellicosting LLC, 980 Chicago Road, Troy, MI 48083-4226]*. However I am not aware of any similar results for hybrids.
Methodology/ Results	Result Appropriateness	48	Jacovides	I realize that you cannot publish confidential information that you obtain from OEM's, but I think it would be useful to show the results to Ford and Toyota before making the report public. They are much more likely to find errors than the review panel and it may prevent any arguments after the report is made public. I understand that this a policy matter, but getting their input seems reasonable to me
Methodology/ Results	Result Appropriateness	49	Miller	At best, the levels of assumptions that are made in a study of this magnitude provide costs that are directionally correct. During the conference call on March 8, 2011, it was stated that the study commissioned was for absolute costs as opposed to range estimates. However, this gives the study results more credence than the assumptions can support. It was also stated, in the same conference call, that a manufacturer had been asked to provide costs for one component and that the cost differential to that developed in this study was 5%. This further supports the concern with reporting the cost results of the analysis as absolutes.

Methodology/ Results	Result Appropriateness	50	Miller	• Concerns regarding validation have been stated consistently throughout this review. Teardown analysis, development of process flow diagrams, analysis of comparable parts where available, etc., are excellent methodologies. However, a number of assumptions have gone into the methodology used to develop the manufacturing costs from these process flow diagrams and the validation of these assumptions are not documented in this paper. Of particular concern are the assumptions around sourcing (directed by the EPA), product maturity, development of burden rates by piece of equipment, direct labor cost calculations and the application of component size ratios as the primary scaling factor for manufacturing cost in other vehicle applications. Recommendations: • For those components/ assemblies which most impact vehicle cost, provide range estimates. Without looking at more detail, a proposal for these ranges can not be made. However, the cost developers for this study should be able to provide such ranges as are appropriate based on sensitivity testing. • Where components are most likely to be sourced outside the United States, costs need to be adjusted for sourcing pattern. The sourcing pattern may be a cost reduction or cost increase dependent upon a number of factors. • In the direct labor calculation of the mean manufacturing labor wage for a component or assembly (page 32), it is unclear whether or not the various labor wage rates are weighted by the calculated number of employees in that classification to obtain a weighted average. If this has not been done, direct labor costs need to be re-evaluated. There are significant wage differentials between the various classifications with general assembler being the lowest paid. (The same applies to the indirect labor costs.)
Methodology/ Results	Result Appropriateness	51	Ramaswamy	The results of the study are appropriate for the given scope, assumptions and inputs.
Methodology/ Results	Result Appropriateness	52	Ramaswamy	The description/report of the validation of the costing methodolgy is not sufficient. The report does say that experts have been consulted in determining the costs of various components, but little validation has been shown (in the report) of cost validation at a subsystem or system level. The overall costs developed by FEV would present a greater punch if there were examples of the comparison of their system/subsystem costs with other costs that have been published in literature.
Methodology/ Results	Result Appropriateness	53	Ramaswamy	FEV and Munro have the tools necessary to do a sensitivity analyses of the costs with respect to different variables of interest. Further analyses could include refinement/correction of some of the assumptions around this study (as mentioned in this review) and studying how the overall system costs are impacted by those changes.

Methodology/ Results	Approach used in Scaling	54	Bohn	The approach used in scaling cost of the powersplit technology to other vehicle classes appears reasonable and shows no reason that it may be not accurate. The actual numbers placed into the scaling routines may be off, and result in turn may be off, but the approach is reasonable.
Methodology/ Results	Approach used in Scaling	55	Bohn	The methodology for using power-split component costs in other hybrid technologies is reasonably and appropriate since several components are common, but scaled. As mentioned above, there are currently no published electric machine rating standards for automotive applications. The electric machine in the P2 topology has (or likely may have) a different load profile than that used for the power-split topology where engine power is split through the two electric machines instead of just one in the P2. To that point using the normalized cost of the electric machines ($/peak watt) from the power-split in the P2 topology is reasonable, but the machine rating/sizing may not directly translate. The battery costs will be equivalent between the two on peak power/energy, scaled as described in the report.
Methodology/ Results	Approach used in Scaling	56	Jacovides	Scaling for a vehicle with identical architecture but with higher power is not as simple as it appears. Results are given on page 132 (pdf*) [Footnote 7: Page numbers refer to the pdf not the pages in the report]* for the HVAC system where the fixed cost of the electronics is, correctly, taken out. However the compressor cost appears to be scaled as the power. This is not correct since the material may indeed be scaled as the power but the labor is not.
Methodology/ Results	Approach used in Scaling	57	Jacovides	Similarly the cost of the electrical machines should not be scaled as power. As stated above scaling for the P2 should be made on the basis of torque and duty cycle. I understand that two designs were made for a 30kW generator and for a 60kW motor. It was said during the conference call that using these designs the data were extrapolated for different size vehicle. This can only be done if the motor and generator have identical torque and duty cycle profiles. This is highly unlikely and so someone with electrical machine design experience needs to develop parametric results for the motor and generator separately. Also as stated above one cannot use power for scaling a slow speed machine used for the P2

Methodology/ Results	Approach used in Scaling	58	Jacovides	The NiMH battery scaling is done correctly. A possible weakness is that as an alternative to reducing the number of cells to estimate a smaller system, one may choose to use a larger number of smaller cells. Regarding the electrical machines and the compressor I suggest that a separate small study be undertaken to determine the scaling factor. I suspect it will be between two extremes, .a) scale as power and b) scale material as power and leave labor and overhead the same. Things get even more complex if a different architecture is used. The approach used here for the P2 architecture is directionally correct but the results will not have the accuracy that the Ford Fusion comparison has with its ICE counterpart.
Methodology/ Results	Approach used in Scaling	59	Jacovides	The treatment of the Li-ion battery (LIB) raises a number of questions 1.What is the available energy? Typically the SOC variation is limited in order to obtain life. For hybrids like the Prius the swing is from about 50% to 60%. The GM Volt battery swing is 30 to 80%. Scaling the LIB to the same nominal kWh assumes that the life of the LIB will be comparable. Some discussion is needed that the life will not be compromised 2.It is not clear what size battery is costed for the P2. Page 126 (pdf) states that the battery from the Avante is 0.954 kWh and this battery was costed on table D13 at $1399. Increasing the energy by 270/180 and scaling the costs as energy the P2 battery should cost $2098. Please explain whether the cost of the P2 battery is $1399, $1798 or $2098. To add to my confusion table F2 shows a battery of 0.9117 kWh for the mid large (Fusion size vehicle). Also table A4 shows $1690.43 for the High Voltage Traction Battery Subsystem. I am sure I am missing something but it needs to be clarified for the reader 3.The estimated cost of the cells given in D-13 for a 0.954 kWh battery of $1020 seems reasonable at roughly 1000 $/kWh
Methodology/ Results	Approach used in Scaling	60	Miller	The use of ratios to develop sizing for HEV components such as traction motors, high traction batteries, etc. as described in the paper is appropriate and can be used effectively to estimate material costs and investment in equipment.

Methodology/ Results	Approach used in Scaling	61	Miller	• Concerns with using the size ratio scaling methodology for certain other cost estimates is documented in other sections of the response. For convenience, they are repeated here:-Certain elements of overhead cost such as salaries and front office costs are not impacted, or at most minimally, by part size. -Direct labor costs are more closely tied to part complexity than to part size. -While part size will impact certain areas of indirect labor, such as material handlers, it will have a lesser impact on number of supervisors, quality inspectors, etc. Like direct labor, these numbers are more closely tied topart complexity than size.-The same concerns exist with establishing component costs for the P2 HEV powertrain components using manufacturing cost to component size ratios (page 127). • The issues addressed above regarding scaling methodology apply equally to the P2 manufacturing cost calculations.
Methodology/ Results	Approach used in Scaling	62	Miller	Recommendations: • Re-evaluate the assumptions around use of a scaling factor to better define those costs which are scalable and those which are not. • Assuming the validity of the approach to costing using manufacturing cost to component size ratios, provide background data supporting this assumption. • As outlined above, review the application of scaling factors, especially for manufacturing cost and burden. The methodology described in the paper yields a result that should be considered as one end of a range estimate. The other end of the estimate should be developed by applying scaling factors to material cost and investment in equipment and holding the other costs constant. If it is necessary to state an absolute cost, the pick a middle ground between these two numbers based on expert opinion.
Methodology/ Results	Approach used in Scaling	63	Ramaswamy	For most of the components, the approach used in scaling the cost of power split technology to other vehicle classes is reasonable and likely to yield reasonable results.
Methodology/ Results	Approach used in Scaling	64	Ramaswamy	The one potential exception (and it is stated as potential, because the approach is not well explained in the report) is the scaling of the high voltage battery parameters across the the different vehicle classes. This needs to be better explained and justified, particularly because this one component is responsible for the bulk of the cost of the hybrid powertrain.
Methodology/ Results	Approach used in Scaling	65	Ramaswamy	Given that the overall cost of the hybrid powertrain is so sensitive to this one component, this reviewer feels that greater care is needed in developing this cost. Conversely, there is considerable detail in the report on the costs for much more minor components, and although that is not a bad thing, the appropriate scaling of the battery system needs to have more effort put into it.

Methodology/ Results	Approach used in Scaling	66	Ramaswamy	Although the scaling for the most of the components across the different vehicle classes seems reasonable, one big item that is not explained clearly is the high voltage battery. Given that it is the single most expensive subsystem within the hybrid powertrain, more care needs to be put into ensuring that this is done in a reasonable manner, and the report needs to explain how this was done. The last paragraph on page 132 talks about the "common run-time" parameter that is used to scale the battery system across vehicle segments. This parameter needs to be defined, and the report should have more of an explanation why the value of 0.0168 hours was used, and how it translates to the other parameters (power rating, energy rating) that define a battery
Methodology/ Results	Approach used in Scaling	67	Ramaswamy	In Table E-2, the nominal pack voltage for the subcompact passenger vehicle is quite low, namely 148V. Could other, potentially cheaper power electronics technologies be used at this battery voltage?
Methodology/ Results	Approach used in Scaling	68	Ramaswamy	There is a small discrepancy between some of the numbers in Table E-2 as compared to those in Table D-3. For example, for the Fusion Hybrid, Table D-3 lists the net power as 142kW, whereas Table E-2 lists it as 140.6kW. Similarly, the engine power is listed as 116kW in Table D-3, but as 114.8kW in Table E-2. Even a rounding of the numbers doesn't make them the same.
Editorial Content	Sufficient Detail/Appropriate Appendices	69	Bohn	The report is sufficiently detailed for a reader familiar with the subject report to understand the process and conclusions. Each of the sections provides a very detailed, pedagogical approach on the rationale of systems and subsystem functions, components and assessed costs.
Editorial Content	Sufficient Detail/Appropriate Appendices	70	Bohn	The tables inserted in the report are, of necessity, very small font with many values in a small area making it somewhat difficult to read in 8.5" x 11" printed format. The electronic format was easier to read and understand, zooming in on one column at a time. No change is needed for this in the report format, but possibly extracted column highlighting significant results would add clarity. A great deal of effort was expended to produce this space efficient report in a readable number of pages (sufficient detail without being too long.)
Editorial Content	Sufficient Detail/Appropriate Appendices	71	Bohn	The appendices are appropriate. The cost model template is sufficient for the appendix.
Editorial Content	Sufficient Detail/Appropriate Appendices	72	Jacovides	I would like to see a clear definition of what is assumed to be the Indirect cost (IC). Is everything not included in Step 7 MAQS on page 21 assumed to be covered by IC? I realize that assigning an IC factor is beyond the scope of this report but it should be made clear what is included. Also it should be made clear that no allowance was made for a different IC factor for parts sold by suppliers and made by the OEM's.

Editorial Content	Sufficient Detail/Appropriate Appendices	73	Jacovides	A minor editorial point deals with Page 10 figure A1. I would clarify the planetary gear set by showing ring, planets and sun clearly. Also remove the gap between the differential to show that the two gears mesh. Further label the output of the differential as going to vehicle wheels not coming from the wheels
Editorial Content	Sufficient Detail/Appropriate Appendices	74	Jacovides	Page 9 makes a good point up front …based on current automotive and/or surrogate industry manufacturing operations and processes, it is acknowledged that a reduction to the costs presented is very likely based on both product and manufacturing learning. Projected technology cost reductions, as a result of learning, are not covered as part of this analysis.
Editorial Content	Sufficient Detail/Appropriate Appendices	75	Jacovides	Page 21.Item #8, Market Place Crosscheck, is a good idea but needs further explanation and the report should show results. Comparison with FEV in house experts seems less than satisfactory.
Editorial Content	Sufficient Detail/Appropriate Appendices	76	Jacovides	Page 37 uses labor rates from BLS. Since lithium ion batteries are not made in the US it would be good to say what labor rate was used for the Li-ion battery. Some of the operations need to be made in low grade clean room
Editorial Content	Sufficient Detail/Appropriate Appendices	77	Jacovides	I would be interested to find out how the electrical machines are cooled for the split power. Oil cooling is used for the P2 and coolant fluid is used for the power electronics but I doubt that coolant was used for direct cooling of the motor and generators
Editorial Content	Sufficient Detail/Appropriate Appendices	78	Miller	Although a substantial amount of detail is included, there are a number of things that should be added to the report to substantiate the process and conclusions. As outlined in a number of questions above, these details are necessary to validate the processes and underlying assumptions used to arrive at the cost conclusions. These details include:-Validation of the Munro & Associates software including methodology and results •Validation and sensitivity testing (or results of the testing) of the FEV cost algorithms •A worked example showing the detail behind each number in the MAQS costing sheet. •Sensitivity analysis for a sampling of the components and assemblies in the cost analysis. •Data supporting the assumption that manufacturing costs can be calculated as a ratio of component size. •Clarification of the calculations for direct labor cost.
Editorial Content	Sufficient Detail/Appropriate Appendices	79	Miller	With the exception of the last item [Clarification of the calculations for direct labor cost.], all of the appropriate documentation should be provided as appendices or as links to other papers/detailed analytical data.

Editorial Content	Sufficient Detail/Appropriate Appendices	80	Ramaswamy	In most cases, sufficient detail has been provided for a reader familiar with the subject report to understand the process and conclusions. Exceptions are: • Rationale for assuming the high voltage battery is manufactured in the United States-Development of the ED&T costs for different subsystems, particularly that for control systems-Validation of the calculated costs at a subsystem/system level • Scaling of the battery system across different vehicle classes Cost for the high voltage DC/DC converter doesn't appear to be included
Editorial Content	Editorial Issues	81	Bohn	There is a divergence in the electrical engineering world on the proper use of the term for electrical distribution 'omnibus'. The classic spelling of the word has only one 's' as in 'bus'. The other spelling is also accepted as 'buss'. There is no direct reference to point of divergence since the word 'electrical bus' was first used. No action required, just pointing out that there are two accepted spellings, the first coming from the origin of the word 'omnibus'. The link below shows a survey of the percentage of respondents on their preference/where they were educated: http://www.gearslutz.com/board/so-much-gear-so-little-time/15867-buss-bus-where-you-learned-3.html
Editorial Content	Editorial Issues	82	Bohn	Pagination and grammar in general are very consistent and acceptable.
Editorial Content	Editorial Issues	83	Jacovides	No comments- everything seems very well done
Editorial Content	Editorial Issues	84	Miller	The general organization of the paper is clear.
Editorial Content	Editorial Issues	85	Miller	The following are areas where typographical errors or other editorial issues exist:-Page 16—Item 2 net to the last line. "Develop" should read Development" •Page 35—next to the last paragraph references a template in Appendix E.4. This Appendix could not be found in my copy of the paper. This may just be a labeling error, but none of the pages in the appendix appeared to be the template referenced.•Page 42—Next to the last paragraph, 2cnd sentence.FOB (freight on board) is usually designated as FOB, destination—supplier pays the shipping costs or FOB Factory—customer takes control of the product and pays the shipping cost. Note that in Europe, FOB is always referred to as "Free on Board". Assuming you mean the receiving company pays the freight, the more common term would be FOB Factory.

Editorial Content	Editorial Issues	86	Ramaswamy	In most cases, sufficient detail has been provided for a reader familiar with the subject report to understand the process and conclusions. Exceptions are: • Rationale for assuming the high voltage battery is manufactured in the United States-Development of the ED&T costs for different subsystems, particularly that for control systems • Validation of the calculated costs at a subsystem/system level • Scaling of the battery system across different vehicle classes • Cost for the high voltage DC/DC converter doesn't appear to be included
Editorial Content	Editorial Issues	87	Ramaswamy	The overall report is well organized. There are a few minor typographical/grammatical issues. These are included in detail in section Grammatical/Typographical Errors 1.Page 10, 2nd line, replace "advance" with "advanced" 2.Page 11, 3rd line, replace "value" with "valve" 3.Page 18, 3rd line, replace "standardize" with "standardized" 4.Page 18, paragraph 2, 1st line, replace "very" with "vary" 5.Page 19, paragraph3, 5th line from bottom, replace "develop" with "developed" 6.Page 21, extra bullet point in Scenario #2 7.Page 52, last paragraph, replace "Too" with "To" 8.Page 52, last paragraph, replace "truck" with "trunk" 9.Page 56, 2nd paragraph, replace "approximate" with "approximately" 10.Page 91, 3rd paragraph, replace "acknowledge" with "acknowledged" 11.Page 97, 1st paragraph, replace "VEV" with "HEV"
Additional Comments	Next Steps	88	Jacovides	Here are some unsolicited improvements and possible next steps: As discussed above under f) have small study made on how to scale electrical machines and the compressor to distinguish between scalable and fixed costs.
Additional Comments	Next Steps	89	Jacovides	It would be good to check with Ford as to the accuracy of the results. Although their volume is not up to 450k they should be able to give you an estimate. For comparing the P2 costs check with Honda or GM, which produce similar architectures although, without a clutch between the engine and transmission. More problematic will be a check with the GM on their two mode hybrids. They have higher power and one additional gear, but they seem to be much more expensive. As I said earlier the numbers check with the Prius that we studied, but we were puzzled by the GM figures. Although the Fusion is bigger the Prius data are a couple of years old and Toyota had not reached the 450k volume.

Additional Comments	Next Steps	90	Jacovides	I would use the scaling exercise for the Volt and the Leaf. These are much different vehicles but have components that have been included in this study. Then check with GM and Nissan on costs.
Additional Comments	General Observations	91	Jacovides	Accurate calculation of the cost of new technology is very important to EPA since it needs to relate it to fuel consumption reductions. The recent history of these efforts is summarized in three reports [Footnote 1,2,3: 1: EPA420-R-08-008 March 2008; 2: EPA-420-R-10-010 April 2010; 3: EPA-420-R-09-020 December 2009]. Until recently the approach was to ask OEMs and suppliers the cost of technologies and by taking several samples and probing to create reasonable estimates of the cost to manufacture. This approach was taken in reference 1 and also by an NRC Committee to study an "Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy" [Footnote 4:http://www8.nationalacademies.org/cp/CommitteeView.aspx?key=48843] .
Additional Comments	General Observations	92	Jacovides	I was a member of this committee and during our discussions we thought that a better approach would be to take apart the components of a new technology and analyze how much each component would cost. Such an approach would include no only the cost of labor and materials but all other "manufacturing" costs. Reference 2 and 3 are examples of such an approach and deal with vehicles with conventional power trains and, in my view, confirm the accuracy of the process.
Additional Comments	General Observations	93	Jacovides	The present report deals with hybrids and my evaluation will deal with the report as it calculates manufacturing costs. Of course in evaluating new technology EPA is charged to estimate not the manufacturing cost but the cost to the consumer to determine the cost to the consumer. Traditionally this was done using the so called Retail Price Equivalent (RPE) factor. The present report uses a factor called Indirect Cost (IC) multiplier. Establishing the multiplier is a highly controversial process and an EPA's attempt is given in [Footnote 5: EPA-420-R-09-003 February 2009]. The controversy as discussed in reference 4 is that EPA tends to come up with a small factor and OEM's with a larger one. Also OEMs insist that a different factor should be used for technologies bought from suppliers and technologies manufacturer in house. Since the present report does not address this issue, I will limit my remarks to the estimation of the "manufacturing" costs as described. However since the EPA will use this factor in its regulatory process, the end result will likely underestimate the final cost to the consumer
Additional Comments	General Observations	94	Miller	It is clear that a great deal of detail and effort has gone into FEV's analysis and preparation of the report.
Additional Comments	General Observations	95	Miller	The use of vehicle/component teardowns is an integral part of the analysis and recognized by the industry as an excellent means of cost analysis. Likewise, the development of detailed process flow charts used in the detailed costing is a well accepted practice.

Additional Comments	General Observations	96	Miller	The report analysis relies heavily on a number of data bases and models that are necessarily quite complex. However, validity testing of the Munro & Associates software which is fundamental to the development of the cost estimates is not documented. Additionally, tests that have been performed to validate the FEV data bases and the costing algorithms are not included.
Additional Comments	General Observations	97	Miller	Recommendation: Since these data bases are integral to the study, include the detailed methodology, including worked examples, used to validate these data bases. Hypothesis testing of assumptions concerning burden rates, product maturity, etc. and sensitivity analysis to demonstrate correlation to actual component costs should be a part of the study. It is recognized that providing all the supporting detail in a paper of this magnitude would be excessive. However, a link to the data could be included similar to the one for OTAQ documents (page 126). If the data is considered proprietary, then examples tracing both a simple and a complex component/assembly through the process demonstrating how the various costs were derived should be included in an Appendix or as a separate document.
Additional Comments	General Observations	98	Miller	The process for defining and apportioning manufacturing burden costs such as front office salaries down to a single machine on the plant floor is questionable. Recommendation: It would be more acceptable to apply the developed burden rates at a manufacturing process/component level.
Additional Comments	General Observations	99	Ramaswamy	Table A-1 has a calculation of the percent decrease/increase in cost of adding the power split system to different vehicle segments. It would be more appropriate to calculate the percentage increase as compared to the base non-hybrid vehicle cost, instead of calculating the increase with respect to the mid/large size vehicle segement cost.
Additional Comments	General Observations	100	Ramaswamy	Nowhere in the paper (for example, section D.7.1 makes no mention of it, and neither do Tables D-5 or D-6) could this reviewer find the mention of the high voltage DC/DC converter (which converts the voltage from approx 300V to approx 600V, and subsequently utilized by the traction motor and generator), which is used in the Fusion Hybrid. The corresponding cost for this part is also not mentioned.
Additional Comments	Battery Manufacturing	101	Ramaswamy	The report assumes that the battery will be manufactured in locations in North America. Although this reviewer understands this to be a constraint from the EPA, this is not a reasonable assumption. There is no large scale automotive NiMH manufacturing in North America currently and there are few plans for the same. Although there are more examples of Li Ion battery manufacturing in North America, it is questionable if Li Ion will be the battery of choice for hybrid vehicles. In this reviewer's experience/knowledge, the NiMH battery will continue to dominate the HEV market, while Li Ion will dominate the PHEV/EV market.

Additional Comments	Power Split Systems	102	Ramaswamy	The report talks about the applicability of the power split hybrid system to the sub-compact, small, large and minivan vehicle segments. It should be clarified that this group covers small SUVs, such as the Ford Hybrid Escape, which is one platform that clearly already supports this hybrid platform.
Additional Comments	P2 Hybrid Systems	103	Ramaswamy	P2 Hybrid System 1. Although the EPA provided the direction to reduce the maximum system torque/power by 18-19%, the rationale for this isn't clear. Without this rationale, a meaningful comparison between the cost figures for the power split system and those for the P2 system cannot be made 2. Why was it felt that the Li Ion battery would be more appropriate for the P2 hybrid? Li Ion batteries have much better energy density than NiMH batteries, so for applications that require large battery energy (such as PHEVs or EVs), it is understandable to use Li Ion packs. However, for the P2 application, the required kWH of the battery (from Table F-2) was less than that for the power split application (from Table E-2). Given this, the selection of the Li Ion technology for the P2 system is not well justified.
Additional Comments	Cost Analysis Observations	104	Ramaswamy	In Figure B-1, why isn't the BOM updated after step 6, when additional information has been gained about the component after its disassembly?
Additional Comments	Cost Analysis Observations	105	Ramaswamy	Page 50, first paragraph refers to 19,149 parts, and it wasn't clear what the 19,149 parts stand for? Are these 19,149 battery packs?
Additional Comments	Cost Analysis Observations	106	Ramaswamy	It isn't too clear how the engineering design costs for various components/systems have been calculated. a. For example, in section D.2.2, how has the engineering design cost for the Atkinson engine and the control system for it, and the calibration for it been calculated/estimated? b.Similarly, how is the engineering design cost for the electronics controllers, for the software for the battery system, for the mechanical design of the battery system been estimated? The actual numbers that have been presented in the tables appear to be too low. c.In Table D-11, why is the ED&T for the traction battery assembly so high ($49) compared to that for the control module (listed as $4)? The relative engineering effort for the control module is not 12 times less than that for the design of the mechanical assembly

Additional Comments	Cost Analysis Observations	107	Ramaswamy	In general, FEV and Munro are to be commended for the detail that they have shown in this approach to determining hybrid system cost. The use of linked MAQS worksheets that allow the component costs to be rolled up to subsystem and system costs is a powerful tool, that can be used to do sensitivity analysis further down the line. However, the best system is only as good as the inputs/assumptions that drive it. Some of the assumptions used in this report(e.g. battery technology and size, manufacturing location, system power)that are key in determining overall system cost have to be carefully thought through and considered during future rulemaking by the EPA.

Appendix A: Charge to Peer Reviewers

Charge to the Peer Reviewers of EPA's Parallel Hybrid Technology Cost Report

EPA's *Parallel Hybrid Technology Cost Analysis Report* is another key milestone in an extensive effort being carried out by FEV, under contract with EPA, to estimate the costs of technologies likely to be used in meeting future light-duty highway vehicle greenhouse gas (GHG) emissions standards. The report details the methodologies used by FEV and its subcontractor(s) to determine the incremental manufacturing cost of one particular LD emission control technology – a power-split parallel hybrid drivetrain, such as found in the Toyota Prius and Ford Fusion Hybrid. In addition to detailing the cost results of power-split technology, this report details the scaling of this technology to other vehicle classes, and establishes how the cost of major power-split components can be used to inform the cost model for other types of vehicle technologies, such as P2 hybrids.

No independent data analysis will be required for this review. Instead, EPA is seeking the reviewer's expert opinion on the methodologies and cost results of this study, and whether they are likely to yield an accurate assessment of the true cost of the technology. We ask that each reviewer comment on all aspects of the report. Please organize all responses according to the charge questions for each of the two categories listed below.

1. Methodology/Results:

    a. Is the methodology documented in the report generally reasonable and likely to yield accurate results? Is any bias likely to be introduced to the results due to methodological issues? If so, please indicate the direction of this bias and potential remedies.

    b. Please identify any general flaws inherent in the scope of the study. Do you feel the results would be altered if the scope were more limited or expanded? Please explain.

    c. Are all appropriate inputs for the study being considered? Conversely, are all inputs considered in the study appropriate? Please cite any particular inputs or assumptions made by the study that you feel are inappropriate or likely to bias the results and how they could be remedied, with particular emphasis on sources of information used in determining labor rates, material prices, manufacturing burdens and other key factors.

    d. Are the assumptions embedded in the model that affect projected cost or performance reasonable? Such assumptions might include learning curve, economies of scale, scaling parameters such as weight and power, labor rates, plant scaling, and material costs.

    e. Are the results expected of the study appropriate for the given scope, assumptions, and inputs? Are there other results that could be derived from the analysis that would support or contradict those cited by the study? Is appropriate validation made on the costing methodology and results? Please expand on any recommendations that you would make for analyses of study results.

f. Is the approach used in scaling the cost of power-split technology to other vehicle classes appropriate and likely to yield accurate results?, Is the methodology for using the cost of power-split components in other hybrid technologies appropriate and likely to yield accurate results?

2. Editorial content:

a. Is sufficient detail provided in the body for a reader familiar with the subject report to understand the process and conclusions? Are appropriate appendices included? Please specify any specific content that you recommended be added or removed.

b. Please comment on any editorial issues that should be addressed in the report, including any comments on general organization, pagination, or grammar and wording.

In preparing comments, please distinguish between recommendations for clearly defined improvements that can be readily made, based on data or literature reasonably available to EPA, and improvements that are more exploratory or dependent, which would be based on information not readily available to EPA. Comments should be clear and detailed enough to EPA readers or other parties familiar with the report to allow a thorough understanding of the comment's relevance to material provided for review.

Additionally, EPA requests that the reviewers not release the peer review materials or their comments until the Agency makes its report/cost model and supporting documentation public. EPA will notify the reviewers when this occurs.

If the reviewer has questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If the reviewer has any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory (schenk.ruth@epa.gov or 734-214-4017).

Appendix B. Peer Reviewer CVs/Resumes

Theodore P. Bohn

Educational Background

M.S. 2003	Electrical Engineering, University of Wisconsin-Madison Electric Machine Design, Power Electronics and Controls
B.S. 1994	Electrical Engineering, University of Wisconsin-Madison Power Electronics, Electric Machines and Control Systems
A.S. 1982	Electrical Engineering Technology, Herzing College

Professional Experience

1999 – Present Electrical Engineer

Argonne National Laboratory, Lemont, IL

Mr. Bohn is a principal investigator in the Vehicle Systems Section of Argonne National Laboratory's Center for Transportation Research. His team is responsible for advanced vehicle testing and evaluation, modeling and systems analysis, and hardware-in-the-loop (HIL) development of hybrid vehicle technologies. He has been designated the *de facto* electric machines and power electronics expert, in a vehicle systems context, for the DOE National Laboratory system. His current assignments include positioning Argonne as the lead national laboratory in plug-in hybrid vehicle research within DOE.

The following lists of achievements and responsibilities are derived from current and past projects within the CTR Annual Operating Plan tasks, as well as from the current position description.

Achievements:

Technology Crosscut: Supported by funds from several DOE sponsors, this effort bridges research on component-level plug-in hybrid vehicle (PHEV) power electronics/motors at Oak Ridge National Laboratory (ORNL), through Advanced Power Electric Machines Projects (APEEM); thermal studies at the National Renewable Energy Laboratory (NREL); and the Energy Storage Tech Team (ESTT), with the FreedomCAR Vehicle Systems (VSATT) work performed at Argonne.

- Interacted with the FreedomCAR APEEM tech team, as well as ORNL, to develop methods for benchmarking high-speed, automotive-grade electric machines and power electronics for PHEVs.
- Constructed, on the basis of a previous proof-of-concept scaled design, a fully capable 55-kW fractional slot, segmented stator, surface permanent magnet prototype motor with an Argonne-motor fabricator-university team. This motor met FreedomCAR targets for cost, mass, operating temperature, and performance (being validated at present) goals. Three prototype motors were constructed to study effects on losses for different stator winding techniques. One of these motors was integrated into a production Lexus RX400h rear motor gearbox and is scheduled to be integrated into an Argonne PHEV prototype vehicle for evaluation.
- Provided technology transfer and information dissemination of state-of-the-art in power electronics and electric machines to FreedomCAR tech teams and OEM partners, as well as component vendors.

- Procured sample OEM electric machines and transaxles from all of the current production hybrid vehicles e.g.., Prius, Lexus, Accord, Civic, Escape, etc). Each of these machines has been modified to connect to a conventional bench dynamometer to catalog key electrical and mechanical parameters commonly used by motor designers. Loss components, such as mechanical/gear loss, windage, and magnetic hysteresis losses, are also part of the catalog of measured motor metrics.
- Generated open-source electric machine motor-drive control software as part of benchmarking the OEM machines described above. These software and benchmarking methods are used to support the SAE Task Force on electric machine rating methods for hybrid vehicle motors.

PHEV Technology Platform Development:

- Created a low-cost, real-time, robust, data collection system for PHEVs based on physical sensors, Global Positioning System (GPS) tracking, and interrogating vehicle CAN bus data; uploaded system to a server via WiFi link (ARDAQ).
- Exploited the surplus computing power of the processor used in ARDAQ to run a Real-time In-Vehicle Emulation Toolkit (RIVETS) vehicle model to emulate a PHEV while driving a conventional vehicle, by using in-vehicle sensors as model inputs.
- Designed, procured, and constructed several custom battery packs based on state-of-the-art battery technologies, such as A123 Systems lithium-nanophosphate chemistry.
- Initiated a research effort to develop PHEV energy storage systems with in-house-derived battery state-of-charge tracking algorithms, which are usually proprietary and not adjustable/tunable by the user, as required for PHEV experiments.
- Created a TTR (through the road) parallel hybrid platform capable of all-electric operation at highway speeds, to be used as a research tool to develop electric/gasoline energy-blending strategies, develop Smart Charging communication techniques, and serve as a benchmark platform for PHEV electric motors and large-capacity batteries. Vehicle uses PSAT-based in-house vehicle-control algorithms.
- Designed and constructed a flex-fuel-powered series PHEV prototype vehicle that contains Vehicle-to-Grid bi-directional power flow charging capability as a tool to evaluate/develop control algorithms, various battery sizes/types, and electric machines. This vehicle and evaluation of component technologies are all in support of SAE J1711, J1772, and J2293 standards development.
- Supported a U.S.-Swedish PHEV technology collaboration that included rapid redesign and upgrading of the Volvo Recharge PHEV concept vehicle to include Vehicle-to-Grid intelligent charging capability. This project is an example of Argonne tech transfer.
- Created the Argonne Advanced Powertrain Embedded Controls Systems (APECS) laboratory to develop many of the controller- and software-enabling applications needed to support the goals of the PHEV research program at Argonne.
- Received Argonne Pacesetter Award for efforts to market Argonne “brand” for PHEV research innovation; as a result, Argonne was named the DOE PHEV Lead Laboratory.
- Worked closely with Argonne Technical Services Division (TSD) to produce marketing materials (e.g., press releases, web updates, brochures for sponsors/conference attendees, DVD-ROMs of data and publications). Hosted a full-sized booth at several professional conferences to aggressively promote CTR transportation programs to the engineering and environmental policy community.

Vehicle Technology Validation and Benchmarking:

- Collaborated with Continental Automotive to validate, in a production vehicle, a prototype 14-V alternator synchronous rectification system that replaces the stock

alternator regulator and effectively is bona-fide “bolt-on fuel economy improvement device” (by measurably reducing accessory load losses) (~1.5 mpg).
- Implemented an EMI-resistant Rogowski Coil-based AC power measurement system to overcome challenges in the electrically “noisy” HEV test environment.
- Demonstrated the use of a novel Gigantic Magneto-Resistive (GMR) effect field sensor embedded in an integrated power module for an HEV traction inverter to sense current inside the power electronics, where a convention probe will not work.
- Developed world-class in-situ torque sensors, incorporating EMI noise-resistant digital telemetry, to measure pulse-by-pulse engine torque without affecting the functionality/accuracy of the vehicle. This was accomplished by replicating the engine flywheel and matching mass and inertia with instrumented force bridges and wireless sensor power transfer.
- Created innovative, non-invasive torque sensor located inside the transmission input shaft by hollowing out the center of the shaft and adding internal strain gauges.
- Successfully procured each of the production hybrid vehicles within the stringent DOE/GSA guidelines and numerous justification letters required by all parties involved. These include the 2007 Hybrid Camry, 2006 Civic Hybrid, 2005 Honda Accord Hybrid, 2004 Toyota Prius, as well as 170,000 mile end-of-life-study (used) hybrids such as 2000 Honda Insight CVT, and 2002 Toyota Prius.
- Created a real-world dynamometer driving simulator based on physical HEV pedals and a computer-based vehicle model. This device is used for the APRF Driver training program, which develops the eye-foot coordination of new vehicle operators to more accurately follow the EPA drive cycle trace. Vehicle parameters and drive cycles are selectable and feedback on driver accuracy is scored; this information is logged into the central host computer. This is also a quality assurance measure.
- Designed and built baseline robotic driver for repetitive vehicle testing at the APRF. System used air-electric brake pedal actuators and direct “by wire” input control to the HEV accelerator pedal command. A newer system is now being constructed with a faster control computer, faster actuators, and better control algorithms.

Hardware-in-the-Loop:
- Participated on initial concept, design, and construction of the Mobile Advanced Technology Testbed (MATT).
- Conceptualized, designed, and implemented a MATT “virtual inertia” electric motor that not only allows the power rating of the motor to be scaled to emulate smaller HEV motors, but the system can dynamically mimic different inertial driveline components/motors via torque sensors and real-time torque feedback equations.
- Participated in a team that created first HIL experiment at Argonne. Based on the bedplate dynamometer, the pre-transmission parallel hybrid diesel-electric hybrid powertrain used an in-house-built constantly variable transmission.
- Constructed and commissioned an axial flux motor (10 kW), HIL test stand that evaluated mechanically field-weakened wheel motors for future HEV powertrain designs. Powertrain was scaled to one-quarter of total road-load, for one of 4 wheel motors.
- Constructed both 120 kW battery HIL test facilities inside the Advanced Powertrain Research Facility (one slow response, one fast response), with battery liquid coolant chiller and environmental chamber for air-cooled tests.
- Initiated new PHEV energy storage system research area for active combination of ultracapacitors, via power electronics, with Li-ion battery experiments for lower-cost, more-robust energy-storage systems for PHEVs.
- Developed new, novel, and robust current regulation algorithms for maintaining ultracapacitor state of charge (SOC) under highly dynamic operating conditions.

- Worked with OEM component vendors to study (and reduce) costs of boost converter magnetic components for electronics used in capacitor/battery studies.

Advanced Vehicle Technology Competitions (AVTCs):

- Worked with AVTC team to collect competition vehicle performance data and reduce it to a set of scored results for the 1999 FutureCar Competition.
- Created a new set of competition rules for the 2000 FutureTruck competition, as well as annual revisions of these rules through the 2004 FutureTruck final year.
- Worked with AVTC team to modify FutureTruck competition rules to match the goals of ChallengeX competition (2005–2008).
- Conducted team on-site inspections and inspections of all participating vehicles at the competition to ensure a safe FutureTruck student vehicle competition for five years of its existence (2000–2004).
- Created high-voltage systems safety and mechanical design "best practices" guideline document used in safety training for the ChallengeX student vehicle designs.
- Responsible for all competition vehicle electrical safety inspections for ChallengeX (2005–2008).
- Worked with highly experienced automotive engineers and academics to organize and host the first ever SAE Formula Hybrid competition, May 3-5, 2007. Responsible for overall competition safety as well as high voltage vehicle safety.

Laboratory Directed Research and Development (LDRD):

- *Engine Waste Heat Recovery, System-Level Study:* Collaborated with university researchers to investigate total quantity of heat recoverable from engine exhaust and coolant loop. Validated heat flux model showing as much as 7% of the total energy input, or 10% of the total waste heat, could be recovered under an arbitrary city driving load cycle (using Argonne Prius vehicle test data). For the assumptions used in this model, these percentages correspond to increasing the useable engine output from 43 kW (at the drive shaft) to 55 kW (drive shaft + electrical generation).
- Studied advanced spray pattern and micro-channel/mini-channel heat exchangers, along with system-level simulation based on Toyota Prius hybrid vehicle actual drive cycle. Recovered waste heat energy converted to electricity via turbo-expander/generator and added to electricity available for traction power in hybrid powertrain. Future work to implement technology in on-road hybrid was proposed, but unfunded.

Work-for-Others: Worked as point of contact and participant in several Work for Others and Technical Services Agreements for outside companies, including:

- Oak Ridge National Laboratory: Instrumentation of 2004 Toyota Prius power electronics drive system for its component benchmarking activities
- General Electric: Hybrid Delivery Truck powertrain testing and development
- Hyundai: PHEV and in-depth HEV benchmarking
- SK Battery: Battery hardware-in-the-loop evaluation and tech transfer/training of test methods to SK Battery, Inc.
- University of Alabama- Birmingham: Created a fully instrumented Ford Escape Hybrid for the university's newly formed hybrid vehicle research lab. Trained faculty and graduate students on details of internal power flow of this vehicle, along with the cutting edge custom torque sensors as well as the turn-key National Instruments turn-key data collection system.

Responsibilities:

- Design and implement experiments that advance the state of the art for hybrid electric vehicle technology.
- Participate in research teams performing complex testing of advanced powertrain subsystems and vehicles, including, battery packs, motors, imported production vehicles, and purpose-built research vehicles.
- Gather and analyze data collected from complex testing of engines, battery packs, motors, and vehicles.
- Prepare technical reports and papers that describe the results of R&D on hybrid electric vehicle technology. Present these results at relevant conferences.
- Supervise technicians and students working on equipment in the Advanced Powertrain Research Facility.
- Determine technical goals, provide organizational-logistical support, and maintain a high level of safety for Advanced Vehicle Technology Competitions.
- Provide DOE sponsors with technology updates and progress summaries of Argonne research.
- Foster relationships with automotive industry component vendors, government agencies, and academia that enhance the hybrid technical community's base knowledge about hybrid vehicle advancements

2000–2004 Renewable Energy Program Manager/Pre-doctoral Researcher
University of Wisconsin-Madison, Madison, WI
Mr. Bohn was the Renewable Energy Program Manager at University of Wisconsin-Madison, College of Engineering, responsible for fundraising, information dissemination, the teaching of power electronics design for renewable energy applications, and the development of curriculum and accompanying text/reference books. As a pre-doctoral researcher, he worked on developing electric machine and power electronics component models used in the Argonne-PSAT system toolkit.

Responsibilities:

- Developed transient response electric motor model for PSAT toolkit.
- Taught course in power electronics design for renewable resources at junior/senior level.
- Raised funds to support renewable energy education program.
- Developed curriculum for undergraduate renewable energy education.
- Managed financial, human/labor, and equipment resources to achieve student design project goals.
- Developed control systems for characterizing interior permanent magnet electric machines, such as the motor in the Toyota Prius.

Achievements:

- Raised $50K in funds to start up renewable energy education program.
- Developed power electronics curriculum for renewable energy applications and associated text/reference book.
- Delivered custom-developed transient electric motor model and simulations for PSAT toolkit.
- Designed, built, and tested prototype low-cost/high-performance soft magnet surface PM motor for HVAC applications.
- Installed 1 kW of wind, solar/photovoltaic (PV), and fuel cell energy on-site resources.

1999–2000 Senior Design Engineer
Power Designers LLC, Madison WI
Mr. Bohn designed and developed a modular, low-cost interlaced battery management system module, called PowerCheq, to manage large battery systems, such as in a hybrid transit bus. He also designed off-road vehicle drive systems, as well as hybrid vehicle power management and high-power/rapid battery chargers. Before leaving Power Designers Corp (PDC) for graduate school, Mr. Bohn initiated work on fuel cell power conditioning power electronics.

Achievements:

- Produced low-cost reliable stationary charger for Kwang Yang Motor Company (KYMCO) electric scooters to reduce emissions in Taiwan. Funded by Industrial Technology Research Institute (ITRI).
- Produced demonstration-level fast-charge system for electric scooters in Taiwan, with communication from battery management system to charger, including method to automatically bill owner of scooter being charged.
- Built proof-of-concept PowerCheq battery equalization module, now in high-volume production.
- Participated on team that designed and built prototype PowerCharge 10-kW battery charger used in industrial lift truck charge stations, as well as ISE Corporation's hybrid buses.
- Designed low-cost sensing and communication interface for PowerTrac battery monitoring system.

Responsibilities:

- Produced promotional materials and represented Power Designers at trade shows/conferences.
- Tracked state of the art in power electronics products and competitive assessments of similar products produced by Power Designers.
- Produced feasibility reports for Power Designers marketing group.
- Designed power electronics circuits for commercial electric vehicles.
- Developed test system software for prototype battery monitoring systems.
- Developed burn-in fixtures for higher-volume-production electronic devices.

September 1982–1992 Engineering Associate- Senior Technical Specialist
Fermi National Accelerator Laboratory, Batavia, IL

Achievements:

- Commissioned 5,000-amp custom-built prime mover and protection system on superconducting solenoid for Colliding Detector Facility (CDF) experiment.
- Designed custom-application specific integrated circuit robust enough to survive radiation levels at the beam aperture for silicon microvertex detector (SVX) and sensitive enough to count individual electrons of signal.
- Designed quench detection/protection system for $6M superconducting solenoid and quench recovery system.
- Produced prototype and sufficient quantity of custom waveform generators for quadrapole steering magnet power supplies in superconducting Tevatron accelerator to correct for higher-order harmonics beam orbit instabilities.

Responsibilities:

- Designed, installed, and commissioned electronic apparatus to support experiments at CDF.
- Oversaw quality assurance and documentation of installed systems.
- Oversaw trouble shooting and maintenance of mission critical systems on experiments (e.g., Tevatron, CDF, D0 Muon line).
- Characterized radiation hardness and performance degradation of Application-Specific Integrated Circuit (ASIC) signal conditioning devices for Silicon Vertex (SVX) detectors.
- Performed periodic power system performance/quality upgrades for detector electronics.

Other Relevant Work Experience

2003–2004 **Caterpillar Corp., Peoria, IL:** (subcontractor) Research Engineer

- Constructed open source code controller on prototype dynamometer to develop standardized test procedures to measure critical electrical parameters of production interior permanent magnet motors; led to the characterization of Caterpillar custom motors.

1997–1998 **Hyperdyne Corp., Madison, WI:** President, Co-founder of S-type Corporation

- S-type Corporation founded with colleagues to compete for Small Business Innovation Research grants (SBIRs). Research projects included such topics as development of algorithms to track battery state of charge, state of health, and instantaneous power capability of electric vehicle batteries. Proof-of-concept products included a power electronics unit for a higher-efficiency electronic “fish fence” to contain migration of invasive non-native species that can cause unnecessary fouling of water inlet hardware.

1996–1997 **Industrias Murrell, Guadalajara, Mexico:** Electrical Engineer Consultant

- Designed proof-of-concept range-extended clean hybrid industrial burden carrier, legal for use as delivery vehicle in Mexico. Project sponsored by Mexican government to reduce emissions in Mexico City by producing a delivery vehicle capable of driving from remote warehouse to downtown on propane-powered internal-combustion (IC) engine, then electric mode for delivery of goods down narrow streets where conventional delivery trucks will not fit.

1995–1996 **Columbia Par Car, Reedsburg, WI:** Electrical Engineer

- Started as consultant hired to resolve noise-vibration-harshness (NVH) problems arising from use of new 4-stroke engine in golf cart design, for Mazda spin-off joint product. Responsible for implementing electric drive systems in custom tram vehicles, industrial burden carriers, and specialty golf carts. Qualified potential charger and drive electronics for future products. Performed range and durability benchmark studies.

1994–1995 **Kohler Company - Generator Division, Kohler, WI:** Researcher/Electrical Engineer

- Developed proof-of-concept solid-state generator set based on latest state-of-the-art components, such as coaxially wound boost power transformers, for market study.

1994–1994 **GM-Advanced Technology Vehicles, Torrance, CA:** Electrical Engineer

- Worked on high-power inductively coupled battery charger for EV-1 electric car as an extension of university research. Initiated series hybrid APU for RE-29 transit bus to study low-noise, low-emission range-extending technologies, via reduced auxiliary loads.

1994–2004 **EVRx Electric Vehicle Design/Development, Madison, WI:** Owner/Consultant

- Electric vehicle design consulting service founded as a result of connections and contacts made through DOE Advanced Vehicle Technology Competitions. Focus of the enterprise was on energy storages systems, power electronics/machines, and controls.

1989–1994 **University of Wisconsin-Madison, High Energy Physics Department:** Electrical Engineer

- Continuation of Fermilab-based experiment apparatus design. Developed very high speed trigger processor systems (1 GHz throughput) for the D0-Muon detection system at the Tevatron proton-antiproton collider at Fermilab. Worked as part of a team on wire chamber particle detectors for the (proposed) SuperCollider in Waxahachie, TX, as well as detector electronics for the Large Hadron Collider (LHC) at CERN, France.

1982–1982 **Kohler General Corp., Sheboygan Falls, WI:** Engineering Intern

- Led efforts to design, construct, program, and evaluate a low-cost programmable controller for a polystyrene thermal expansion press that produced formed packing inserts for Craftsman Tools. Project used (at the time, cutting edge) a Zilog Z-80 single-chip microprocessor on $200 single-board computer as the basis for a low-cost alternative to a $2,000 commercially available Texas Instruments Programmable Logic Controllers (PLC).

1977–1999 **Sunshine Satellite Systems, Cleveland, WI:** Founder/owner/operator

- Started as apprentice for communications equipment repair/refurbishment business. New digital era satellite communications afforded an opportunity to start a small business based on installing and maintaining Very Small Aperture Terminals (VSAT) for retail stores (ground satellite terminal), as well as home-based satellite receivers.

Professional Societies (chosen to be consistent with job responsibilities)

Society of Automotive Engineers (SAE)
Institute of Electrical and Electronics Engineers (IEEE)
IEEE Power Electronics Society (PELS)
IEEE Industrial Applications Society (IAS)

Honors and Awards

1997 Granger Outstanding Power Engineering Student Award (undergrad)
2001 Focus on Energy $2,000 Scholarship for design of grid-tied power inverter
2002 Granger Outstanding Power Engineering Student Award (graduate)
2003 Tong Innovative Student Design Award (low-cost third-world electric vehicle)
2005 Recipient of an SAE Transactions Paper Award (Characterization of Variability in 4WD Dynamometer Testing Results Due to Tie-Down Methods)
2007 Argonne Pacesetter Award for establishing Argonne as DOE lead on PHEV research
2008 Society for Technical Communications "Distinguished Award" for PHEV informational materials (brochures and posters), developed with Argonne TSD staff
2008 Nominated for R&D100 Award for ARDAQ real-time data acquisition system

Patents

US Patent applied for — Real-time In-Vehicle Emulation Toolkit
This patent applied for as enhancement of Argonne's Real-time Data Acquisition System (ARDAQ) that allows users to emulate future technologies, with a conventional production vehicle, in real time.

Organizational Activities (subset)

Session Chair of Advanced Battery Technology Committee, SAE World Congress 2008
Session Chair of Fuel Cell Committee, SAE World Congress 2007
General Committee of the 23rd Electric Vehicle Symposium, Anaheim CA, 2007
Organizer of International Electric Machines Designer Conference, 2003
SAE Electric Machine Rating Standards Task force—*current*
SAE J1772 Electric/Hybrid Vehicle Conductive Charging Equipment Standards—*current*
SAE J1711 Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles—*current*
SAE J2238 Energy Transfer System for Electric Vehicles: Functional Requirements, System Architectures, and Communication Messaging—*current*
Peer reviewer for IEEE conferences (APEC, IAS, PESC, IEMDC) and SAE World Congress

Community Service (subset)

Volunteer — Introduce a Girl to Engineering Day (IGED) program 2007, 2008
Volunteer — Mentor for Future Energy Challenge design competition 1999–present
Volunteer — Habitat for Humanity 1990–present
Volunteer — Adult Literacy Program 1985–1990

Publications: Journal Articles and Book Contributions

(listed as separate document)

LINOS J. JACOVIDES

A native of Paphos, Cyprus, Dr. Linos J. Jacovides received Bachelor's and Master's degrees in Electrical Engineering, from the University of Glasgow, Scotland, and a Doctorate in Generator Control Systems from the Imperial College, University of London, in 1965.

Dr. Jacovides was most recently Director, Delphi Research Labs, from December of 1998 until he retired in January of 2007. This was the Central research operation for Delphi with a budget around $20M and involved a group of about 90 researchers dealing with advanced projects - 5 to 15 year horizon. The staff has mostly doctorates in physical sciences and engineering with at least 10 Fellows of IEEE, SAE, and the American Physical Society. In this post, he was responsible for R&D in the following areas: Manufacturing Processes, Materials, Devices, Mechatronics, Polymers, and Systems. Unlike some Corporate Research Labs the funding was based on voluntary contributions from the Business Units (BUs). Although in many industrial labs such a mechanism leads to short term projects, an agreement was reached that 30% of the budget would be allocated to long term exploratory projects at the discretion of the Lab Director. The remaining 70% was for projects that were approved by the BUs. This worked very well until the company declared bankruptcy in 2005.

He joined General Motors Research and Development in 1967 after a two-year assignment at the Defense Research Laboratories in Goleta, California. He held several positions at General Motors Research becoming one of GM's youngest executives at age 35. He became department head, electrical engineering in 1985.

His areas of research were the interactions between power electronics and electrical machines in electric vehicles and locomotives. He worked on some of the electric vehicles of the 60's to the 80's at GM. By the 80's he argued against commercializing the EV1 maintaining that the batteries were not ready for the market. At Delphi his technical interests were on fuel economy, electronics and alternative fuels. He is the author of ten peer reviewed articles, two patents and several internal research reports. He edited the first SAE special publication on Electric Vehicles.

Since retirement he acted as a consultant to Delphi for several months, to help formulate Delphi's strategy on fuel economy. Since September of 2007 he is also on four Committees of the National Academies to assess various aspects of vehicle technologies for improving fuel economy. His contributions are in the area of vehicle propulsion (internal combustion, hybrids, fuel cell and plug-in hybrids). He is also a member of the Visiting Committee for the EE Dept at Michigan State University

He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), where he served as President of the Industry Applications Society in 1990. He is also a 43 year member of SAE and was recently elected Fellow for his work on electric propulsion. He was a representative of Delphi at the Industrial Research Institute.

Resume

Education

B.Sc. 1961, (1st Class Honours, Electrical Engineering) University of Glasgow, Scotland -- Prize for " .. the most distinguished graduate of the year in the engineering faculty".
M.Sc. 1962, University of Glasgow -- Thesis on synchronous machine theory.
Ph.D. 1965, Imperial College, University of London, England-- Thesis on electric power grid stability control systems.
Goethe Institut German for foreign students - summers of 1960 and 1961

Employment

Consulting

- Expert witness in case against the Army
- Taught classes on electric drives at University of Michigan
- Member of Board of Directors Novolyte Technologies –Electrolytes for Lithium ion batteries
- National Research Council - Economy Assessment of Resource Needs for Development of Fuel Cell and Hydrogen Technology & Potential Impacts of Plug-In Hybrid Electric Vehicles.

Delphi

- Special assignment to formulate Delphi strategy on fuel economy 2007-08 (4 months)
- Director Delphi Research Laboratories (Executive Position) 1999- 2007

General Motors Research Laboratories

- Chief Scientist Delphi Energy and Engine Management 1994 - 99
- Head, Electrical and Electronics Department, 1988- 99 (Executive Position)
- Principal Research Engineer, EE Dept., 1987-1988
- Asst. Department Head, EE Dept., 1985-1987 (Executive Position)
- Senior Staff Research Engineer, EE Dept., 1975-1985 (Executive Position)
- Senior Research Engineer, EE Dept., (Special bonus awards 1969, 1970, 1972), 1970-1975,
  Research Engineer, EE Dept., 1967-1970

GM Defense Research Laboratories, Goleta, California, 1965-1967
1959 Summer intern Ferranti Limited Manchester. UK
1961 Summer intern Siemens & Halske Karlsruhe. Germany

Professional Societies

IEEE Fellow 1990
IEEE Industry Applications Society

Society President 1990 Vice President 1989 Secretary 1988
Chairman of the Industrial Power Conversion Systems Department 1986-88
Chairman of the Industrial Drives Committee 1984-85

IEEE Power Electronics Society – past member
IEEE Magnetics Society – past member

SAE (past chairman of both the Electric Vehicle Committee and the Electrical and Electronics Systems Committee)
Institution of Electrical Engineers, (IEE) England – past member

Invited Talks

- An Electrical Engineer in the Automobile Industry
- Student Activities Committee
- IAS Annual Meetings 1986 and 1987

Technical activities

- Organized many technical sessions in technical meetings for both the SAE and the IEEE. Starting in 1970
- Initiated a series of Global Technical conferences where Delphi engineers could present their advanced work
- Technical Vice Chair for Convergence in 2000 and 2004. convergence is the premier conference for automotive electronics and the Vice chair is actually the person in charge of the program
- National Research Council. Committee memberships
    - Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy 2007 to 2010
    - Review of the FreedomCAR and Fuel Research and Development Partnership, Phase 3. 2009 to 2010
    - Transportation Research Board. Chair of PANEL SP20-83(04) Effects of Changing Transportation Energy Supplies and Alternative Fuel Sources on State Departments of Transportation. 2009 to 2012

Publications

1. "A Critical Evaluation of AC Motor Drives for Traction," B. V. Murty and L. J. Jacovides. Presented at the 20th Intersociety Energy Conversion Engineering Conference, Miami, FL, Aug. 18-23, 1985.

2. "Brushless Motor Drive for In-Tank Fuel Pump," B. R. Patel, L. J. Jacovides, J. G. Neuman. Presented at the 1984 SAE Congress Feb. 27 Mar. 2 1984. SAE Paper No. 84445.

3. "A Cycloconverter-Synchronous Motor Drive for Traction Applications," L. J. Jacovides, M. F. Matouka, and D. W. Shimer. IEEE Trans. Industry Applications Vol. IA-17 #4, pp. 407-418, (Jul/Aug. 1981).

4. "An Improved Triggering Method for a High-Power Cycloconverter-Induction Motor Drive," IEEE Trans. Industry Applications Vol. IA-15 #5, pp. 472-481, (Sept./Oct. 1979).

5. "Electric Vehicle Simulation Program," R. H. Nelson, L. J. Jacovides, F. J. Schauerte, and E. J. Woods. Presented at the International Electric Vehicle Symposium, Philadelphia, PA, October 2-5, 1978. Published at the Conference Proceedings.

6. "Digital Simulation of a High-Performance AC Drive System, Part II," S. D Rajan, L. J. Jacovides and W. A. Lewis. IEEE Trans. Industry Applications Vol. IA-10 #3, pp. 397-402, (May/June 1974).

7. "Digital Simulation of a High-Performance AC Drive System, Part-I," S. D. Rajan, L. J. Jacovides and W. A. Lewis. IEEE Trans. Industry Applications Vol. IA-10 #3, pp. 391-396, (May/June 1974).

8. "Analysis of a Cycloconverter Induction Motor Drive System Allowing for Stator Current Discontinuities," IEEE Trans. Industry Applications Vol. IA-9 #6, pp. 206-215, (Mar/Apr 1973).

9. "Analysis of Induction Motor Drives with Non-sinusoidal Supply Voltage Using Fourier Analysis." IEEE Trans. Industry Applications Vol. IA-9 #6, pp. 741-747, (Nov/Dec 1973).

10. "Effect of Excitation Regulation on Synchronous Machine Stability," L. J. Jacovides and B. Adkins. Proc. IEE Vol 113, #6, pp. 1021-1033 (June 1966).

11. "The Effect of Regulation of Excitation on the Stability of Synchronous Machines." Ph.D. Thesis, Imperial College, University of London, August, 1965.

12. "The Inductance Matrices of the Salient Pole Synchronous Machine," M.Sc. Thesis, University of Glasgow, Scotland, September, 1962.

Patents

Induction Motor Fabrication Method 3,705,971 Dec. 12, 1972
Method of Induction Brazing a Complex Assembly 4,443,678, Apr. 17, 1984

Reports

There are several research reports that are GM or Delphi confidential. However the titles of three recent ones may be relevant.

1. Alternative Fuels and the Impact on Delphi - Global Issues. Delphi Research Labs report No 385 2006
2. Alternative Fuels and the Impact on Delphi – Regional Assessment. Delphi Research Labs report No 400. 2006
3. Fuel Economy – Strategic Analysis. Assessment of Delphi's Strategy to improve vehicle fuel economy. Innovation Technology Office 2008

LINDA M. MILLER
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Grosse Ile, Michigan 48138 | Cellular: 313-218-6075

CAREER SUMMARY

A results-driven senior manufacturing executive with extensive experience in automotive component manufacturing, business planning and supply base development. Demonstrated ability to build consensus among diverse groups through creation of common goals and objectives. Significant experience in global operations management, operations consolidation and new program management. A strong track record of delivering objectives through the effective development of people, ability to handle difficult Union relationships and effective communication skills.

PROFESSIONAL EXPERIENCE

FORD MOTOR COMPANY, Dearborn, MI 1973-2007
Automotive Manufacturer

Director of Manufacturing, Powertrain Operations 2005-2007
Responsible for the performance of 9 engine, casting, forging and electronic components plants in the United States, Mexico and Canada with a combined business of $950M.

- Developed a strategic plan for standardization of key systems across all plants that delivered 15-20% annual improvement in cost and quality performance metrics.
- Led Union negotiations around out-sourcing of non-critical indirect labor and streamlining of classifications that resulted in reduced operating costs.
- Championed the Powertrain Environmental and Quality Councils and Six Sigma efforts working to achieve common operating systems across all powertrain plants.
    - Key elements of operating systems were agreed upon and are under implementation.
- Chaired the Powertrain People Development Committee (PDC) and Manufacturing Leadership Program that led to identification and development of a diverse group of high potential employees.
- Acted as Co-chair of the steering committee for Women in Manufacturing and through participation in the Executive Council on Diversity was the formal / informal mentor for over 25 men and women in manufacturing.

Director of Manufacturing, V-Engine and Casting, Powertrain Operations 2002-2005
Responsible for the performance of seven engine and casting plants in Canada and the United States with a combined business of $700M.

- Developed cost, quality and safety processes resulting in cost improvements that averaged 8% annually across all plants, warranty and internal quality improved over 10% per year and safety metrics improved over 15% annually.
- Successfully negotiated and led implementation of the idling of a forging plant and an aluminum casting plant.
- Led a cross-functional task force that enabled development and production of a cost – effective all new 3.5L engine. Innovative engineering design and manufacturing processes saved $1,800 per unit.
- Teamed with the Group Vice-president of Manufacturing to develop and launch the Women in Manufacturing organization as one of Ford's employee resource groups.

FORD MOTOR COMPANY, (continued)

Director of Manufacturing, Casting Operations, Powertrain Operations 2000-2002

Responsible for the performance of all eleven casting and forging plants world-wide with a combined business of $400M. In addition, responsible for divesture and / or consolidation of facilities wherever feasible.

- Initiated lean manufacturing principles which enabled the US and Canadian plants to achieve 5% performance improvements annually and meet operating budget for the first time.
- Led divestiture or joint venture partnerships for plants in Argentina, New Zealand and the aluminum plants in Canada and created strategy for the closure of four plants in the US and Canada that resulted in closure of three and pending closure of 4^{th}.
- Managed the Staff Castings Manufacturing Engineering Group responsible for development of new manufacturing technology and for providing manufacturing technical assistance for supply base.
    - Teamed with outside supplier and product engineering that developed the first high volume, high pressure die cast aluminum cylinder block for Ford.
- Ford Senior Representative in the American Foundryman's Society.
    - Led the effort for the society to become more inclusive by changing the name to American Foundry Society.
    - Advanced the development of student education through participation in the Foundry Education Foundation (FEF) seminars as a keynote speaker.

Director, Manufacturing Business Office, Ford Motor Company 1998-1999

Directed the work of the world-wide business offices for vehicle and powertrain manufacturing in the development of a world-wide manufacturing business plan that would complement the global product development cycle plan.

- Achieved economies of scale by moving all four cylinder engine manufacturing development to Europe and consolidating v-engine work in the United States.
- Identified opportunities for the introduction of flexible manufacturing technologies that maximized the ability of manufacturing to react to late cycle plan changes.
- Assessed the proposed manufacturing plans for South America, India and China and achieved maximum asset utilization.
- Developed the supplier park concept for Ford of Europe that reduced logistic and hourly workforce costs.

Director, Supplier Technical Assistance, Ford Purchasing 1995-1998

Responsible for globalizing and consolidating the various supplier quality and technical support groups in Ford world-wide.

- Developed and implemented a common system of supplier evaluation and performance measurement that enabled effective sourcing of product based on quality and cost.
- Streamlined the organization by eliminating multiple interface points with the same supplier resulting in a 30% reduction in staffing.
- Developed a supplier accessible electronic data base for performance metrics that allowed suppliers to react more quickly to quality trends.
    - Improved supplier quality 40% over three year period.
- Led a team of key suppliers and internal personnel that developed a methodology for warranty sharing between Ford and suppliers which became a benchmark in the industry and significantly reduced Ford warranty costs.

FORD MOTOR COMPANY, (continued)

Plant Manager, Dearborn Engine and Fuel Tank Plant 1993-1994
Managed a three shift plant manufacturing four cylinder engines and all of the steel fuel tanks for Ford cars and trucks. Employment of 1500 union and salary employees. Responsibility also included design cost reduction and new program implementation.

- Negotiated unique operating patterns and developed new technology applications to reduce the original planned investment in a new engine program by 35%.
- Reduced operating costs by 10% while improving engine warranty costs by 11% and becoming the first Ford plant to achieve the Total Quality Excellence award.
- Improved results in the Plant Leadership Behavior Survey by 40% through a series of actions recognizing employee contributions and instituting quarterly small group meetings with all salary personnel with an emphasis on candid dialogue.

Asst. Plant Manager, Cleveland Engine Plants 1991-1993
Responsible for running Cleveland Engine Plant 1 manufacturing the 4.9 and 5.0L engines.

Manufacturing Manager, Essex and Windsor Engine Plants 1989-1991
Responsible for production, quality and manufacturing engineering at the Windsor and Essex Engine plants.

Manufacturing and Plant Engineering Manager, Dearborn Engine Plant 1987-1989
Quality Control Manager, Dearborn Engine Plant 1985-1987
Supervisor, Planning and Material Cost Reduction, Engine Division 1983-1985
Production Superintendent, Dearborn Engine Plant 1982-1983
Inspection Superintendent, Dearborn Engine Plant 1979-1982
Quality Control Engineer, Engine Division 1978-1979
Supplier Quality Assurance Representative, Engine Division 1976-1978
Quality Control Analyst, Engine Division 1973-1976

EDUCATION

MBA, Management, University of Detroit, Detroit, MI 1981
MA, Mathematics**,** University of Kansas, Lawrence, KS 1972
BS, Mathematics, Northeast Missouri State University, Kirksville, MO. 1970

MEMBERSHIPS / AFFILIATIONS

President, University of Detroit-Mercy Business School Advisory Board 1999-present
President, Truman State University Foundation Board 2004-present
Co-Chair, Board of Trustees, Wayne State University / Ford Motor Engineering Management Master’s Program 2000-2006
Member, Women’s Automotive Association International 2004-present
Member, American Foundry Society 2000-2006
Member, Board of Directors, Cleveland Opera 1991-1993
Member, United Way Leadership Giving Council, Canada 1989-1991

AWARDS AND RECOGNITION

Distinguished Alumni Award, University of Detroit-Mercy, Business School 2005
100 Leading Women in the Automotive Industry, Automotive News 2000 & 2005
Spirit of Leadership Award, Women’s Automotive Association International 2004
Alumni of the Year, Truman State University 2002
Magnificent Seven Award, Business and Professional Women’s Club 1997
Pilliod Lecturer, Kent State University 1995

DEEPA RAMASWAMY, PH.D.

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SUMMARY OF QUALIFICATIONS

Extremely motivated and results-driven management, engineering and business development professional with exceptional oral and written communication skills and an extensive background in the following broad-based competencies:

BUSINESS DEVELOPMENT	**ENGINEERING CONSULTING**	**HYBRID SYSTEMS**
PRODUCT DEVELOPMENT	**PROGRAM MANAGEMENT**	**BATTERY SYSTEMS**
RESEARCH & DEVELOPMENT	**SYSTEMS ENGINEERING**	**CONTROLS & ELECTRONICS**
MODEL-BASED ENGINEERING	**SALES & NEGOTIATION**	**RAPID PROTOTYPING SYSTEMS**
DESIGN VERIFICATION & VALIDATION	**EMBEDDED SYSTEMS**	**FAILURE MODES & EFFECTS ANALYSIS**

- One of only a handful of people who have been integrally involved with an OEM production hybrid program from program inception to launch.
- Extensive and professionally recognized engineering and business development skills in the areas of hybrid systems, plug-in hybrids, battery systems and controls and electronics.
- Demonstrated project leadership and program management skills with ability to build talented teams and generate high customer satisfaction.
- Proven capacity to lead large engineering teams in fast-paced product development environments and expeditiously deliver novel complex systems.
- Deep technical expertise in electrical engineering and control systems with the ability to combine project and team management skills with technical expertise to develop and implement high quality solutions.

PROFESSIONAL EXPERIENCE

HYBRID CHAKRA CONSULTING, LLC. – *Canton, Michigan* **May 2009-Present**

Founder and CEO

Founded a consulting company that offered services in the hybrid vehicle, plug-in hybrid vehicle, electric vehicle and alternative energy domains.

- Provided program management, systems engineering, systems architecture, modeling & analysis and embedded controls design consulting support to OEMs, Tier 1s, suppliers and other entities.
- Provided independent reviews of proposals, analyses and reports created by other entities (suppliers, service providers) in these domains.
- Completed projects in the area of battery system management, vehicle control system development and simulation analysis of hybrid system architectures.
- Offered market/technology survey services.
- Offered training in the areas of hybrid controls, hybrid architectures and plug-in hybrids.
- Offered business development services in above listed domains.

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RICARDO, INC. – *Van Buren, Michigan* **July 2007-April 2009**

Chief Engineer, Hybrid Systems, Controls & Electronics

Performed business development and engineering consulting in the domains of hybrid systems, battery systems and controls and electronics. With high-level contacts from over 150 companies nationwide in these fields, developed leads, authored proposals, conducted negotiations and led numerous projects to completion. As a result of exceptional performance, selected to head up the hybrid activities for Ricardo in the US.

- Demonstrated excellent business development ability by winning **$6.6 million of order intake** during tenure.
- Won **Employee of the Month** Award for managing a **$5 million project** and received a very high "Voice of the Customer" **rating of 9.6/10** from the customer.
- Recognized as a top performer and received an **"Exceptional"** performance review rating during annual performance review.
- Identified a market need for Battery Systems development and supported development of business case for the establishment of a **$2 million** state of the art Battery Systems Development Center and organized the well attended Open House.
- Authored numerous proposals in the following topics: hybrid system development, vehicle integration, Plug in Hybrid Electric Vehicle (PHEV) development, battery pack development, battery management systems, active safety control systems, PHEV market studies, model based control system design, electronics development, modeling , simulation of vehicles, design verification and production validation (DV/PV) of components and systems, Hardware in the loop (HIL) testing, dyno testing, vehicle testing.
- Led technological aspects of proposal development for DOE Funding Opportunity Announcement on Transportation Electrification (DE-FOA-0000028), including partner selection and concept definition.
- Developed workplans, established budgets, conducted negotiations with customers and executed projects to maximize the return to the company and to provide high value to the customer.
- Won and led projects including the following:
    - Active Safety Control System development for a major automotive OEM.
    - Conversion of a hybrid vehicle to a PHEV for a major commercial vehicle Tier 1.
    - Market study of the US PHEV market for a major automotive OEM and recommendation of PHEV type and timing.
    - Training in battery technology and systems for a major commercial vehicle Tier 1.
    - Simulation of propulsion systems for a marine Tier 1.
    - Investigation of state of the art communication protocols in a Battery Management System for a Battery Tier 1.
- Provided technical expertise and knowledge to support projects including the following:
    - Review and update of the hybrid technology decision tree on the NHTSA Notice for Proposed Rulemaking (NPRM) for CAFÉ standards for MY 2011-2015.
    - Virtual vehicle development environment for battery systems.
    - A Fuel Economy Demonstrator program for the military.

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FORD MOTOR COMPANY – *Dearborn, Michigan* **1995 – June 2007**

Supervisor, Research & Advanced Engineering 2004 – June 2007

Directly supervised a team of nine experts in the design of architecture and algorithms for next-generation hybrid control systems and guided the work of about 40 engineers in the department. Developed common global control systems across Ford, Jaguar, Land Rover and Volvo products. Ensured smooth technology transfers from advanced engineering to product development. Created work and resource plans to ready new technologies for implementation. Presented the program strategies to upper management.

- Drove a common development process across global brands that maximized product re-use and minimized the resources required for product development with a projected resource reduction of 60%.
- Proposed control system hardware architecture with maximum portability between vehicle configurations that allowed for easy migration across engine, transmission and brake technologies.
- Instilled a sense of team discipline in all work by establishing clear processes, plans and deadlines; fostered strong relationships with production department that shifted team focus to delivering long-term solutions.
- Recognized as **Top Achiever** on performance review rating; consistently received high performance review ratings.
- Led development of an Integrated Modeling Environment, facilitating reuse of Legacy products and enabling model-based control system development, system level simulation and automatic C-code generation.

Supervisor, North American Product Development 2000 – 2004

Promoted to lead development of the powertrain control system for the Ford Hybrid Escape SUV program. Built a superior team of engineers and coordinated interaction with other engineering teams and global suppliers to ensure timely delivery and high product quality. Managed capital, material and travel budget costs of $2 million and coordinated interaction with global suppliers from Japan and Europe. Analyzed impact of intellectual property issues. Reviewed designs, created work plans and employed multiple systems engineering tools. Supervised an engineering team of 17 to create specifications and design the control software for prototype vehicles.

- **Won the Henry Ford Technology Award** in 2005 for leading the team that built the first production vehicle system controller for a U.S. automotive company.
- Developed and launched the company's most complex system in its vehicle lineup to control the hybrid SUV that achieved a 50% improvement in fuel economy for a super ultra-low emissions and AT-PZEV rating; acknowledged with J.D. Power reviews for high quality.
- Established six new processes for controller design and validation including the use of rapid prototyping that reduced development time by 70% and the use of hardware in the loop systems for design verification.
- Formulated supplier strategies and secured the best possible quotes by negotiating statements of work with purchased service suppliers; identified ways to use existing resources that reduced purchase order amounts.
- Featured as a key hybrid powertrain system supervisor in Fast Company and Global Auto Insider magazines.
- Delivered a Ford First product on time that met high quality standards and allowed the company to launch a new product which won the 2005 North American International Auto Show Truck of the Year award.

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Controls Engineer 1998 – 1999

Charged to develop the control system for the company's first production hybrid electric vehicle. Designed high level programs using MATLAB and Simulink software and followed up with automatically generated C code to quickly test designs on actual prototypes. Pioneered the use of the dSPACE MicroAutoBox rapid prototyping system on a production vehicle program that significantly reduced control system development time. Transferred fledgling product technology from advanced research facilities smoothly into production.

Automotive Electrical Engineer 1995 – 1998

Gained extensive exposure to the full spectrum of automotive engineering activities through a two-year rotation program. Benchmarked graphical user interface development tools. Created graphical user interfaces for engine simulation programs. Supported the electrical system launch for the Lincoln Continental's 13 onboard computers. Challenged to apply core engineering knowledge and skills by modeling several electromechanical vehicle components to support vehicle-level electrical simulation.

BUSINESS EXPERTISE

- **Business Development:** Identification of target markets, customer contact and lead development.
- **Proposal Development:** Proposal technical writing, workplan development and resource allocation.
- **Sales and Negotiation:** Review of terms and conditions, Purchase Orders (POs) and "closing the deal" with a win-win attitude.
- **Program Management:** Leading projects and managing within budgeted resources and with high customer satisfaction.

TECHNICAL EXPERTISE

- **Hybrid and Battery Systems:** System architecture, vehicle integration, system prototyping, development, verification and validation.
- **Control Systems:** Algorithms, software and hardware embedded system controls for hybrids, batteries, powertrains and active safety.
- **Computer Modeling/Simulation:** MATLAB, Simulink, C, C++, UML, UNIX, Microsoft Windows and Office, HTML, Saber, Modelica and Tcl/Tk.
- **Systems Engineering Tools:** Requirements, design verification methods and plans, failure mode and effects analysis, robustness analysis, 8Ds, fishbone diagrams, fault tree analysis and design of experiments.

PATENTS AND PUBLICATIONS

- Received five patents with four additional patents pending.
- Authored three SAE conference papers, one ASME conference paper, five IEEE conference papers and two IEEE journal publications.
- Invited speaker at the Detroit Electrochemical Society meeting (joint meeting with Wayne State University COE) in November, 2010.

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EDUCATION AND CERTIFICATION

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN *Champaign, Illinois*

Doctor of Philosophy in Electrical Engineering 1995

Master of Science in Electrical Engineering 1991

INDIAN INSTITUTE OF TECHNOLOGY *Madras, India*

Bachelor of Technology in Electrical Engineering; graduated 1st in class 1989

FORD MOTOR COMPANY *Dearborn, Michigan*

Six Sigma Greenbelt Certification 2003

CITIZENSHIP

U.S.

Appendix C. Peer Reviewer Comments As Submitted

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U.S. Environmental Protection Agency (EPA) Peer Review

of Draft Report, FEV 07-069-303F Dated February 22, 2011
"Light-Duty Technology Cost Analysis Power-split and P2 HEV Case Studies"
Peer Review by Theodore Bohn
March 15, 2011

Overview of the Draft Report

The "Light-Duty Technology Cost Analysis Power-split and P2 HEV Case Studies" describe FEV's methodology for determining incremental, direct manufacturing costs to estimate the costs of technologies likely to be used in meeting future light-duty highway vehicle greenhouse gas (GHG) emissions standards.

The methodology consists of the following approach:

- Cost analysis of the production hardware systems was performed as follows:
    - Tear down of the production hardware systems
    - Evaluation on a part-by-part basis of observed differences in size, weight, materials, machining steps and other parameters affecting cost.
- Use of databases for material costs, labor rates, manufacturing overhead rates, mark-up rates and packaging costs to calculate costs to fabricate individual parts and subsystems which are added together to provide the overall system costs.

Following the costing methodology overview, the incremental cost impact of adding power-split hybrid electric vehicle (HEV) technology to a conventional baseline vehicle was discussed. The analysis is based on the detail teardown and costing of the hardware difference, applicable to the adaptation of power-split HEV technology, found between the 2010 Ford Fusion HEV, and an equivalent equipped 2010 Ford Fusion conventional powertrain vehicle. A description of the hardware required to create the power-split technology is highlighted and details on the costs are captured at various levels.

Specific cost analysis was provided for Integrated Motor/Generator and clutch assembly system costs were broken out for the P2 configuration.

The study concluded that the net incremental/assembly cost impact to the OEM was $ 3,435.01for the power-split topology in the large vehicle segment (Ford Fusion sized chassis), and $3564.66 for the P2 configuration in the same size of chassis.

This reviewer's area of expertise concerns electric machine technology and control of electric machines as well as hybrid control systems. Remarks in this review are subjective and the reviewer's knowledge of actual manufacturing costs vs engineering level component costs is limited to first hand procurement of prototype systems contrasted with cost/performance design goals for electric machines.

In the format of the provided reviewer template, the following comments on the document are offered:

1. Methodology/Results:

Charge Question:	Reviewer Comments:
Is the methodology documented in the report generally reasonable and likely to yield accurate results? Is any bias likely to be introduced to the results due to methodological issues? If so, please indicate the direction of this bias and potential remedies.	• Overall, the draft document presents a generally reasonable methodology that is likely to yield accurate results. • The assumptions used for the P2 HEV system are somewhat subjective on adding the P2 functionality as an 80/20 power sharing between engine and motor for peak conditions. This may introduce a bias in the results of the benefit vs the component cost, or in this case incremental costs. The assumption about engine downsizing is that the base vehicle and the P2 Hybrid will have equivalent performance with increased fuel economy. While peak performance is straight forward to assess for both the baseline and P2 Hybrid versions, the amount of engine blending, depth of discharge of the batteries, etc will affect the assessed fuel economy. • It is difficult to assess the direction of the bias (cost or performance/F.E. mismatch)- i.e. component sizing is cost sensitive and depending on the engine/motor torque blending, component cost may be over stated or understated based on blending assumptions and equivalence the to the base vehicle. • There is no simple remedy for this supposed bias since engine downsizing and component sizing are subjective based on the desired performance attributes to compare the hybrid version to the base vehicle. The assumptions made in the report (section A) are fair, and clearly stated. • As with many vehicle simulations, the component scaling methodologies need validation. In some industries, component scaling is limited to technology or performance ranges. For instance IGBT transistors versus MOSFET transistors are used for two different voltage ranges with some overlap. Even so, the scaling assumptions are bounded by the available voltage limit for the transistors. Scaling up power ratings on an inverter, or battery voltage have impacts on the scaled inverter costs, caused by (for instance) the boundary where one would use MOSFETs for lower voltage and IGBTs for high voltage.
Please identify any general flaws inherent in the scope of the study. Do you feel the results would be altered if the scope were more limited or expanded? Please explain.	• The scope of the document is broad reaching. Expanding the scope of the study would likely introduce more variability with increased assumption. • The scope does not need to be reduced since it covers many aspects on the cost of producing an automobile and reducing the scope would not necessarily increase the validity or accuracy of the study.
Are all appropriate inputs for the study being	• The scope and breadth of inputs used for the study and cost

considered? Conversely, are all inputs considered in the study appropriate? Please cite any particular inputs or assumptions made by the study that you feel are inappropriate or likely to bias the results and how they could be remedied, with particular emphasis on sources of information used in determining labor rates, material prices, manufacturing burdens and other key factors.	assessments are broad and apparently all encompassing. There are many input items on costs, such as labor rates and overhead on labor, which are outside the expertise of this reviewer. To the best of my knowledge, all the inputs used in this study are appropriate. •
Are the assumptions embedded in the model that affect projected cost or performance reasonable? Such assumptions might include learning curve, economies of scale, scaling parameters such as weight and power, labor rates, plant scaling, and material costs.	• Comments in the boxes above discuss some of the bounded areas of assumptions that affect cost and/or performance, such as engine/motor blending. • A somewhat contentious point related to assumptions is the component rating system for electric machines. There is currently no published standard for electric machine rating methods in automotive applications. Peak ratings versus average versus steady state, as well as inlet cooling rates and losses at different operating points are tied up in the assumptions used to compare one electric machine to another after the scaling algorithm. • The model is very comprehensive, and according to the reviewer's teleconference, the authors of this study validated many of the models and component scaling models. • To the best of this reviewer's knowledge, the assumptions used in this study are reasonable. Inputs on materials cost for the study appear to be reasonable to this reviewer.
Are the results expected of the study appropriate for the given scope, assumptions, and inputs? Are there other results that could be derived from the analysis that would support or contradict those cited by the study? Is appropriate validation made on the costing methodology and results? Please expand on any recommendations that you would make for analyses of study results.	• Yes. The results expected of the study are reasonable given the scope, assumptions and inputs. • The net incremental cost for each of the vehicle sizes and two hybrid topologies seems intuitive on cost magnitude, if in fact performance is equivalent. • This reviewer cannot comment on other results that could be derived from the study. • Validation is a very subjective process with regard to the 'level of validity'. After reading the study description, and listening to the authors during the reviewer's teleconference where the validation process was described, it appears that reasonable validation was achieved on the costing results.
Is the approach used in scaling the cost of power-split technology to other vehicle classes appropriate and likely to yield accurate results? Is the methodology for using the cost of power-split components in other hybrid technologies appropriate and likely to yield accurate results?	• The approach used in scaling cost of the powersplit technology to other vehicle classes appears reasonable and shows no reason that it may be not accurate. The actual numbers placed into the scaling routines may be off, and result in turn may be off, but the approach is reasonable. • The methodology for using power-split component costs in other hybrid technologies is reasonably and appropriate since several components are common, but scaled. As mentioned above, there are currently no published electric machine rating standards for automotive applications. The electric machine in the P2 topology

	has (or likely may have) a different load profile than that used for the power-split topology where engine power is split through the two electric machines instead of just one in the P2. To that point using the normalized cost of the electric machines ($/peak watt) from the power-split in the P2 topology is reasonable, but the machine rating/sizing may not directly translate. The battery costs will be equivalent between the two on peak power/energy, scaled as described in the report.

2. Editorial content:

Charge Question:	Reviewer Comments:
Is sufficient detail provided in the body for a reader familiar with the subject report to understand the process and conclusions? Are appropriate appendices included? Please specify any specific content that you recommended be added or removed.	• The report is sufficiently detailed for a reader familiar with the subject report to understand the process and conclusions. Each of the sections provides a very detailed, pedagogical approach on the rationale of systems and subsystem functions, components and assessed costs. • The tables inserted in the report are, of necessity, very small font with many values in a small area making it somewhat difficult to read in 8.5" x 11" printed format. The electronic format was easier to read and understand, zooming in on one column at a time. No change is needed for this in the report format, but possibly extracted column highlighting significant results would add clarity. A great deal of effort was expended to produce this space efficient report in a readable number of pages (sufficient detail without being too long.) • The appendices are appropriate. The cost model template is sufficient for the appendix.
Please comment on any editorial issues that should be addressed in the report, including any comments on general organization, pagination, or grammar and wording.	• There is a divergence in the electrical engineering world on the proper use of the term for electrical distribution 'omnibus'. The classic spelling of the word has only one 's' as in 'bus'. The other spelling is also accepted as 'buss'. There is no direct reference to point of divergence since the word 'electrical bus' was first used. No action required, just pointing out that there are two accepted spellings, the first coming from the origin of the word 'omnibus'. The link below shows a survey of the percentage of respondents on their preference/where they were educated. • http://www.gearslutz.com/board/so-much-gear-so-little-time/15867-buss-bus-where-you-learned-3.html • Pagination and grammar in general are very consistent and acceptable.

No independent data analysis will be required for this review. Instead, EPA is seeking the reviewer's expert opinion on the methodologies and cost results of this study, and whether they are likely to yield an accurate assessment of the true cost of the technology. We ask that each reviewer comment on all aspects of the report. Please organize all responses according to the charge questions for each of the two categories listed below.

In preparing comments, please distinguish between recommendations for clearly defined improvements that can be readily made, based on data or literature reasonably available to EPA, and improvements that are more exploratory or dependent, which would be based on information not readily available to EPA. Comments should be clear and specific enough to EPA readers or other parties familiar with the report to allow a thorough understanding of the comment's relevance to material provided for review.

Additionally, EPA requests that the reviewers not release the peer review materials or their comments until the Agency makes its report/cost model and supporting documentation public. EPA will notify the reviewers when this occurs.

If the reviewer has questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If the reviewer has any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory (schenk.ruth@epa.gov or 734-214-4017).

Peer Reviewer Report

Preamble

Accurate calculation of the cost of new technology is very important to EPA since it needs to relate it to fuel consumption reductions. The recent history of these efforts is summarized in three reports[1][2][3]. Until recently the approach was to ask OEMs and suppliers the cost of technologies and by taking several samples and probing to create reasonable estimates of the cost to manufacture. This approach was taken in reference 1 and also by an NRC Committee to study an "Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy"[4].

I was a member of this committee and during our discussions we thought that a better approach would be to take apart the components of a new technology and analyze how much each component would cost. Such an approach would include no only the cost of labor and materials but all other "manufacturing" costs. Reference 2 and 3 are examples of such an approach and deal with vehicles with conventional power trains and, in my view, confirm the accuracy of the process.

The present report deals with hybrids and my evaluation will deal with the report as it calculates manufacturing costs. Of course in evaluating new technology EPA is charged to estimate not the manufacturing cost but the cost to the consumer to determine the cost to the consumer. Traditionally this was done using the so called Retail Price Equivalent (RPE) factor. The present report uses a factor called Indirect Cost (IC) multiplier. Establishing the multiplier is a highly controversial process and an EPA's attempt is given in[5]. The controversy as discussed in reference 4 is that EPA tends to come up with a small factor and OEM's with a larger one. Also OEMs insist that a different factor should be used for technologies bought from suppliers and technologies manufacturer in house. Since the present report does not address this issue, I will limit my remarks to the estimation of the "manufacturing" costs as described. However since the EPA will use this factor in its regulatory process, the end result will likely underestimate the final cost to the consumer

Detailed comments

Methodology/Results:

Section a. Is the methodology documented in the report generally reasonable and likely to yield accurate results? Is any bias likely to be introduced to the results due to methodological issues? If so, please indicate the direction of this bias and potential remedies.

The methodology is clearly correct and could lead to correct results. As stated above, I am familiar with the approach because it was discussed during the NRC

1 EPA420-R-08-008 March 2008
2 EPA-420-R-10-010 April 2010
3 EPA-420-R-09-020 December 2009
4 http://www8.nationalacademies.org/cp/CommitteeView.aspx?key=48843
5 EPA-420-R-09-003 February 2009

committee on “Improving the Fuel Economy of LDV” and in the references listed earlier. The report, under review, represents a superb implementation of the concept.

The analysis of the Ford Hybrid and cost comparisons with its ICE equivalent is done very carefully and correctly without any bias that I can detect. Interestingly the increase in cost of $3435 that this report comes up with is almost identical to the one we came up for the Prius in the NRC study of $3385. We did that by talking to OEM’s and suppliers. However I want to emphasize that the approach taken by this report is far superior. As long as a detailed design or an actual vehicle is available this is the way to do it. It does require a great deal of industrial engineering skill to estimate the amount of labor, and cost of materials but in the hands of FEV this has produced excellent results.

It should be pointed out that the methodology is limited to the two architectures studied viz. split power hybrids as implemented by Toyota and Ford and to a limited extend on the P2 architecture as implemented by Hyundai. I say limited since there was no design available for the electrical machine in this case. The battery for the P2 was properly analyzed by tear down of an actual unit. Nevertheless the analysis can be extended to other hybrids such as the two types made by GM (two mode and the Malibu ISG) and the Honda Insight

Section b. Please identify any general flaws inherent in the scope of the study. Do you feel the results would be altered if the scope were more limited or expanded? Please explain.

The results of this study cannot properly be evaluated without knowledge of what EPA considers the IC factor to be. I realize that this is not in the scope of the report. However IC factors range from 1.02 to 1.45 as stated in reference 5. Industry RPE factors were estimated in Reference 4 to be 1.5 or 2.0 depending on whether parts were bought or made in house. One can calculate manufacturing costs to the penny but then the end result can vary by a factor of up to two depending on the multiplier

The results for the P2 may be directionally correct, but I am concerned about the sizing of the power electronics and the electrical machine. FEV should have bought a Honda Insight (IMA), available in the US in the spring of 2010, or a GM Malibu (ISG) for a tear down of the electrical system (Power electronics and machine). The duty cycle of the electrical system is very different than that of the power split and so the ratios of copper to iron to magnets will likely be different. Also it seems from Table F2 that the electrical machine was sized based on power. As discussed below torque and duty cycle are the primary determinants of size and hence cost. It should be pointed out that P2 has a clutch which provides two features that the Insight and the Malibu do not have. The clutch can disconnect the engine so that regenerative braking does not have to be reduced to provide for engine friction and can provide an all electric range (AER). The 32.4kW power of the electrical machine will not provide the required torque and power. There should be a statement to the effect that the P2 is not designed to provide an AER

Another problem is the assumption of a 20% vehicle curb weight reduction for the P2 architecture and for all vehicle segments. Such a reduction does not come for free and I found no rationale for this. In reference 4 we found that a 10% reduction in a 3600 lbs vehicle would add around $700. During the conference call it was implied that the P2 electrical systems is lighter. This may not be so and certainly not by 20%. The speed of the P2 electrical machine is not an independent variable and it is much lower than the speeds of the two power split machines. The size of electrical machines is determined by torque and not power and so a slower speed machine will be heavier. Clearly getting an Insight or a Malibu would have given a better estimate.

Another flaw of the study is that it depends on the ability of the people using the study to turn the crank for other vehicles or for vehicles without the detail provided by a teardown. Clearly FEV has demonstrated that it is developing that knowledge, although I am not sure about the accuracy of the electrical systems numbers for the P2. The question then becomes "will EPA need FEV in the future in order to use this work". Based on the conference call with EPA, FEV and the Reviewers, this study will not be used for other architectures so the above point is moot. However I would like to caution that any extension to other architectures needs to be done by skilled manufacturing engineers and cost analysts.

Section c. Are all appropriate inputs for the study being considered? Conversely, are all inputs considered in the study appropriate? Please cite any particular inputs or assumptions made by the study that you feel are inappropriate or likely to bias the results and how they could be remedied, with particular emphasis on sources of information used in determining labor rates, material prices, manufacturing burdens and other key factors.

When it comes to the main part of the report i.e. the comparison between a hybrid and an ICE Fusion everything seems to be done very well. Possible exceptions are in estimating the following costs

1. Development of control software.
2. Integration of the electrical and mechanical parts.
3. Calibration. Hybrid vehicles are more complex and to make performance transparent to the driver is expensive. Safety also requires extensive calibration. Toyota has recalled the 2010 Prius to fix software when braking on ice on bumpy roads. If this can happen to Toyota with 10 years experience on hybrids, it must be taken seriously.

These are upfront engineering costs and by the time production volume has reached 450k units may not be significant. However they need to be added to the cost of the vehicle.

Section d. Are the assumptions embedded in the model that affect projected cost or performance reasonable? Such assumptions might include learning curve, economies of scale, scaling parameters such as weight and power, labor rates, plant scaling, and material costs.

These seem to me to be appropriate. A problem will arise with the next person who runs the model. Will they have the expertise of FEV, which I think is one of the premier automotive engineering firms?

Section e. Are the results expected of the study appropriate for the given scope, assumptions, and inputs? Are there other results that could be derived from the analysis that would support or contradict those cited by the study? Is appropriate validation made on the costing methodology and results? Please expand on any recommendations that you would make for analyses of study results.

The results are reasonable, not only because the actual number is the same as we got in our study but because the costs are estimated with great detail. I am aware of one other company that has used this approach to come up with detailed costs of automotive components[6]. However I am not aware of any similar results for hybrids.

I realize that you cannot publish confidential information that you obtain from OEM's, but I think it would be useful to show the results to Ford and Toyota before making the report public. They are much more likely to find errors than the review panel and it may prevent any arguments after the report is made public. I understand that this a policy matter, but getting their input seems reasonable to me

Section f. Is the approach used in scaling the cost of power-split technology to other vehicle classes appropriate and likely to yield accurate results?, Is the methodology for using the cost of power-split components in other hybrid technologies appropriate and likely to yield accurate results?

Scaling for a vehicle with identical architecture but with higher power is not as simple as it appears. Results are given on page 132 (pdf)[7] for the HVAC system where the fixed cost of the electronics is, correctly, taken out. However the compressor cost appears to be scaled as the power. This is not correct since the material may indeed be scaled as the power but the labor is not.

Similarly the cost of the electrical machines should not be scaled as power. As stated above scaling for the P2 should be made on the basis of torque and duty cycle. I understand that two designs were made for a 30kW generator and for a 60kW motor. It was said during the conference call that using these designs the data were extrapolated for different size vehicle. This can only be done if the motor and generator have identical torque and duty cycle profiles. This is highly unlikely and so someone with electrical machine design experience needs to develop parametric results for the motor and generator separately. Also as stated above one cannot use power for scaling a slow speed machine used for the P2

The NiMH battery scaling is done correctly. A possible weakness is that as an alternative to reducing the number of cells to estimate a smaller system, one may choose to use a larger number of smaller cells. Regarding the electrical machines and the compressor I suggest that a separate small study be undertaken to determine the scaling factor. I suspect it will be between two extremes, .a) scale as power and b) scale material as power and leave labor and overhead the same. Things get even more complex if a different architecture is used. The approach used here for the P2 architecture is directionally correct but the results will not have the accuracy that the Ford Fusion comparison has with its ICE counterpart.

The treatment of the Li-ion battery (LIB) raises a number of questions

1. What is the available energy? Typically the SOC variation is limited in order to obtain life. For hybrids like the Prius the swing is from about 50% to 60%. The GM Volt battery swing is 30 to 80%. Scaling the LIB to the same nominal kWh assumes that the life of the LIB will be comparable. Some discussion is needed that the life will not be

[6] Intellicosting LLC, 980 Chicago Road, Troy, MI 48083-4226

[7] Page numbers refer to the pdf not the pages in the report

compromised

2. It is not clear what size battery is costed for the P2. Page 126 (pdf) states that the battery from the Avante is 0.954 kWh and this battery was costed on table D13 at $1399. Increasing the energy by 270/180 and scaling the costs as energy the P2 battery should cost $2098. Please explain whether the cost of the P2 battery is $1399, $1798 or $2098. To add to my confusion table F2 shows a battery of 0.9117 kWh for the mid large (Fusion size vehicle). Also table A4 shows $1690.43 for the High Voltage Traction Battery Subsystem. I am sure I am missing something but it needs to be clarified for the reader
3. The estimated cost of the cells given in D-13 for a 0.954 kWh battery of $1020 seems reasonable at roughly 1000 $/kWh

Editorial content:

Section a Is sufficient detail provided in the body for a reader familiar with the subject report to understand the process and conclusions? Are appropriate appendices included? Please specify any specific content that you recommended be added or removed.

I would like to see a clear definition of what is assumed to be the Indirect cost (IC). Is everything not included in Step 7 MAQS on page 21 assumed to be covered by IC? I realize that assigning an IC factor is beyond the scope of this report but it should be made clear what is included. Also it should be made clear that no allowance was made for a different IC factor for parts sold by suppliers and made by the OEM's.

A minor editorial point deals with Page 10 figure A1. I would clarify the planetary gear set by showing ring, planets and sun clearly. Also remove the gap between the differential to show that the two gears mesh. Further label the output of the differential as going to vehicle wheels not coming from the wheels

Page 9 makes a good point up front *…based on current automotive and/or surrogate industry manufacturing operations and processes, it is acknowledged that a reduction to the costs presented is very likely based on both product and manufacturing learning. Projected technology cost reductions, as a result of learning, are not covered as part of this analysis.*

Page 21.Item #8, *Market Place Crosscheck*, is a good idea but needs further explanation and the report should show results. Comparison with FEV in house experts seems less than satisfactory.

Page 37 uses labor rates from BLS. Since lithium ion batteries are not made in the US it would be good to say what labor rate was used for the Li-ion battery. Some of the operations need to be made in low grade clean room

I would be interested to find out how the electrical machines are cooled for the split power. Oil cooling is used for the P2 and coolant fluid is used for the power electronics but I doubt that coolant was used for direct cooling of the motor and generators

Section b. Please comment on any editorial issues that should be addressed in the

report, including any comments on general organization, pagination, or grammar and wording.
No comments- everything seems very well done

Section c. In preparing comments, please distinguish between recommendations for clearly defined improvements that can be readily made, based on data or literature reasonably available to EPA, and improvements that are more exploratory or dependent, which would be based on information not readily available to EPA. Comments should be clear and detailed enough to EPA readers or other parties familiar with the report to allow a thorough understanding of the comment's relevance to material provided for review.

Suggestions for next steps

Here are some unsolicited improvements and possible next steps:

1. As discussed above under f) have small study made on how to scale electrical machines and the compressor to distinguish between scalable and fixed costs.
2. It would be good to check with Ford as to the accuracy of the results. Although their volume is not up to 450k they should be able to give you an estimate. For comparing the P2 costs check with Honda or GM, which produce similar architectures although, without a clutch between the engine and transmission. More problematic will be a check with the GM on their two mode hybrids. They have higher power and one additional gear, but they seem to be much more expensive. As I said earlier the numbers check with the Prius that we studied, but we were puzzled by the GM figures. Although the Fusion is bigger the Prius data are a couple of years old and Toyota had not reached the 450k volume.
3. I would use the scaling exercise for the Volt and the Leaf. These are much different vehicles but have components that have been included in this study. Then check with GM and Nissan on costs.

Respectfully submitted

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U. S. Environmental Protection Agency (EPA) Peer Review

Draft Report: FEV07-069-303F Dated 2/22/2011
Title: Light-Duty Technology Cost Analysis Power-split and P2 HEV Case Studies

Reviewer: Linda M. Miller
Review Date: March 14, 2011

To facilitate use of this review, I will first provide some general observations and recommendations. More detail will be provided in the sections of this review that are organized in alignment with the topics and questions in the Peer Review Charge.

General Observations:

- It is clear that a great deal of detail and effort has gone into FEV's analysis and preparation of the report.

- The use of vehicle/component teardowns is an integral part of the analysis and recognized by the industry as an excellent means of cost analysis. Likewise, the development of detailed process flow charts used in the detailed costing is a well accepted practice.

- The report analysis relies heavily on a number of data bases and models that are necessarily quite complex. However, validity testing of the Munro & Associates software which is fundamental to the development of the cost estimates is not documented. Additionally, tests that have been performed to validate the FEV data bases and the costing algorithms are not included.

Recommendation: Since these data bases are integral to the study, include the detailed methodology, including worked examples, used to validate these data bases. Hypothesis testing of assumptions concerning burden rates, product maturity, etc. and sensitivity analysis to demonstrate correlation to actual component costs should be a part of the study. It is recognized that providing all the supporting detail in a paper of this magnitude would be excessive. However, a link to the data could be included similar to the one for OTAQ documents (page 126). If the data is considered proprietary, then examples tracing both a simple and a complex component/assembly through the process demonstrating how the various costs were derived should be included in an Appendix or as a separate document.

- The process for defining and apportioning manufacturing burden costs such as front office salaries down to a single machine on the plant floor is questionable.

Recommendation: It would be more acceptable to apply the developed burden rates at a manufacturing process/component level.

Comments by Charge Question:

1. **Methodology/Results**

Question:
Is the methodology documented in the report generally reasonable and likely to yield accurate results? Is any bias likely to be introduced to the results due to methodological issues? If so, please indicate the direction of this bias and potential remedies.

Response:

- **While the methodologies, for the most part, appear reasonable, there are some areas of concern.**
  - **There is a lack of documentation in the paper proving that the methodologies yield accurate results. While the paper references marketplace validation, no examples are given.**

    Recommendation: Include examples taking developed costs for items such as fuel injector assemblies(Figure C-3, page 45, Sample MAQS Costing Worksheet); extrapolating these to a total cost using the approach outlined in the paper; and then comparing these costs to actual marketplace pricing for the example used. One or two worked examples of this nature would help to validate the overall methodology. Alternatively, include a table, detailed by component/ sub-assembly, showing the methodologies and comparisons used for costing each item.

  - **The costing methodology, as presented, develops costs that are absolute. Given the complex nature of the end product and the manufacturing processes, it would have been appropriate to include sensitivity analysis in the costing detail. If sensitivity analysis has been performed on a sampling of costs, it is not shown in the paper.**

    Recommendation: Assuming sensitivity analysis is available, show the impact of sensitivity analysis in the examples in the paper. If sensitivity analysis has not been performed, then this is an area of detail that needs to be completed. From a manufacturing perspective, sensitivity analysis on high dollar components needs to include scrap rates, mean time to repair of equipment, equipment uptime, etc.

  - **The scaling methodology appears to be overly simplified. For example, scaling factors are applied to labor and manufacturing overhead. The cost of direct labor is more a factor of part complexity than one of size. Also, certain elements of overhead cost such as salaries and front office costs are not impacted, or at most minimally, by part size.**

Recommendation: A deeper review of the approach to scaling needs to be undertaken to insure that costs are not under/over-stated. Again, applying sensitivity tests may help determine whether or not these differences are significant.

Without the documentation noted above, it is not possible to say whether or not bias has been created.

Question:
Please identify any general flaws inherent in the scope of the study. Do you feel the results would be altered if the scope were more limited or expanded? Please explain.

Response:
I do not see any general flaws inherent in the scope of the study. Extrapolation to other vehicle sizes could not be done without the basic underlying detailed studies. However, once the component costs had been developed for the Fusion, the justification for the extensive use of scaling factors to approximate these costs for other vehicle lines does not have the same level of detail as the rest of the study. Whether or not this has been impacted by the scope of the project can not be determined.

Recommendation: Review the application of scaling factors, especially for manufacturing cost and burden. The methodology described in the paper yields a result that should be considered as one end of a range estimate. The other end of the estimate should be developed by applying scaling factors to material cost and investment in equipment and holding the other costs constant. If it is necessary to state an absolute cost, the pick a middle ground between these two numbers based on expert opinion.

Question:
Are all appropriate inputs for the study being considered? Conversely, are all inputs considered in the study appropriate? Please cite any particular inputs or assumptions made by the study that you feel are inappropriate or likely to bias the results and how they could be remedied, with particular emphasis on sources of information used in determining labor rates, material prices, manufacturing burdens and other key factors.

Response:
Although, as explained in the conference call on March 8, 2011, it is EPA policy to perform studies of this nature independent of the OEM's, it would have seemed appropriate to seek validation of the teardown costing from the manufacturer whose vehicle is the basis for this analysis. For a review of other assumptions that are of concern, see the response to the next Question.

Question:
Are the assumptions embedded in the model that affect projected cost or performance reasonable? Such assumptions might include learning curve, economies of scale, scaling parameters such as weight and power, labor rates, plant scaling, and material costs.

Response:
While the majority of assumptions cited in the study are valid, there are a number of assumptions that need to be re-considered. They are as follows:

- The technologies used are considered to be mature. It is more likely that the technology will continue to evolve requiring changes to manufacturing facilities and tooling. The assumption of maturity, for example, impacts a number of underlying cost elements and other assumptions: there are assumed to be no allowances for product/manufacturing learning, scrap rates are minimal, non-recovered E,D&T expense and capital costs are zero, and there are no allowances for equipment end of life costs. All of these stem from the assumption of maturity. At the same time, however, it is assumed that no new or modified equipment maintenance is required (See pages 16 & 17). This is not consistent with equipment at the end of its life cycle. All of the above will cause cost estimates to be understated.

Recommendation: Review the costs impacted by the assumption of maturity. Uplift costs by a percentage factor where appropriate. If the assumption remains that equipment will be at the end of its useful life, then increase maintenance costs over time according to the equipment OEM's guidelines.

- It is assumed that "integration of new technology would be planned and phased in to minimize non-recoverable expenses". This would indeed be the most cost effective decision. However, given the significant requirements for fuel economy improvements and emissions reductions, the need to implement new technology will likely be the over-riding consideration.

Recommendation: Perform cost sensitivity analyses with non-recovered E,D&T and stranded capital in percent increments ranging from 10 to 30 %. Include the results in the paper.

- End-item scrap includes quality defects, rework costs, and/or destructive test parts (page 29). The general mark-up varies from 0.3% to 0.7% depending on part complexity and size (page40, Table C-1). However, it is stated that exceptions are made depending on the part. Examples cited in Section C.4.5.2 include sand and investment casting. These are considered to be "generic" processes and the end-item scrap mark-up is uplifted to 5% in both cases. However, just as in Table C-1, this rate needs to vary dependent upon the part size and part complexity (I am assuming tolerance limits are considered part of part complexity. If not, tolerances need to be considered as another factor in determining scrap rates.) Without a part by part review of the assumptions, the impact to the cost analysis can not be determined.

Recommendation: To test the reasonableness of the scrap percentages, check a random sample of components and compare the end-item scrap rates for those processes to industry standards. Use complexity and size of the parts to adjust averaged rates.

- All sourcing/manufacturing centers are assumed to be in the United States. As discussed in the March 8, 2011 conference call, this is not a valid assumption and can significantly impact cost either negatively or positively.

Recommendation: Review present sourcing patterns, at least for the high cost components and sub-assemblies, and utilize these patterns as the basis for the cost analysis.

- Labor Rates MAQS Costing Worksheet Example (page 46). It can not be determined whether or not any overtime costs were assumed in the labor cost/hour calculation. Overtime costs will vary manufacturer to manufacturer based on Union agreements and/or operating practices. However, in a number of cases (Ford Motor Company for one), shifts of 10 hours per day in the United States would generally include 2 hours of overtime pay. Afternoon shift also has an associated premium cost.

Recommendation: Verify underlying assumptions in the labor rate models.

- Packaging Assumptions: Based on the sample calculation (page 50, Figure C-6), allowances for a percentage of pallets/racks out for cleaning and/or repair (generally around 5%) have not been included. This understates the packaging cost.

Recommendation: Increase the # of packaging units required by 5% where returnable packaging is used.

- Cost of Complexity Assumptions: Based on the volume assumption of 450K per year, although it is not stated in the report, it is assumed that the major complex assemblies: Engine and Transmission as well as Complex Subsystems are produced on dedicated lines. If not, then a cost of complexity factor needs to be added. The 75% combined utilization/efficiency assumption (calculated based on page 37) is reasonable. However, if hybrid components are assembled on the same lines as the baseline products, then this utilization/efficiency is over-stated due to the inherent inefficiencies caused by manufacturing complexity. Note: It should be assumed that hybrid and base vehicles will be assembled on the same line and so this added complexity must be factored into the utilization/efficiency calculation.

Recommendation: Process flow diagrams for complex base-line vehicle assemblies/components should be compared to those developed for HEV vehicle

and adjustments made to the efficiency/utilization percents for HEV based on this comparison.

- **System Scaling Cost Analysis: While the use of ratios to develop sizing for HEV components such as traction motors, high traction batteries, etc. is appropriate and can be used to estimate material costs, the use of these ratios to determine other factors within manufacturing cost such as labor (page 126) is less valid. Part complexity influences these costs more than part size. The same concerns exist with establishing component costs for P2 HEV powertrain components using manufacturing cost to component size ratios (page 127).**

Recommendations:

- **Re-evaluate the assumptions around use of a scaling factor to better define those costs which are scalable and those which are not.**

- **Assuming the validity of the approach to costing using manufacturing cost to component size ratios, provide background data supporting this assumption.**

- **As outlined above. review the application of scaling factors, especially for manufacturing cost and burden. The methodology described in the paper yields a result that should be considered as one end of a range estimate. The other end of the estimate should be developed by applying scaling factors to material cost and investment in equipment and holding the other costs constant. If it is necessary to state an absolute cost, the pick a middle ground between these two numbers based on expert opinion.**

Question: Are the results expected of the study appropriate for the given scope, assumptions, and inputs? Are there other results that could be derived from the analysis that would support or contradict those cited by the study? Is appropriate validation made on the costing methodology and results? Please expand on any recommendations that you would make for analyses of study results.

Response: At best, the levels of assumptions that are made in a study of this magnitude provide costs that are directionally correct. During the conference call on March 8, 2011, it was stated that the study commissioned was for absolute costs as opposed to range estimates. However, this gives the study results more credence than the assumptions can support. It was also stated, in the same conference call, that a manufacturer had been asked to provide costs for one component and that the cost differential to that developed in this study was 5%. This further supports the concern with reporting the cost results of the analysis as absolutes.

Concerns regarding validation have been stated consistently throughout this review. Teardown analysis, development of process flow diagrams, analysis of comparable parts where available, etc., are excellent methodologies. However, a number of assumptions have gone into the methodology used to develop the

manufacturing costs from these process flow diagrams and the validation of these assumptions are not documented in this paper. Of particular concern are the assumptions around sourcing (directed by the EPA), product maturity, development of burden rates by piece of equipment, direct labor cost calculations and the application of component size ratios as the primary scaling factor for manufacturing cost in other vehicle applications.

Recommendations:

- **For those components/ assemblies which most impact vehicle cost, provide range estimates. Without looking at more detail, a proposal for these ranges can not be made. However, the cost developers for this study should be able to provide such ranges as are appropriate based on sensitivity testing.**

- **Where components are most likely to be sourced outside the United States, costs need to be adjusted for sourcing pattern. The sourcing pattern may be a cost reduction or cost increase dependent upon a number of factors.**

- **In the direct labor calculation of the mean manufacturing labor wage for a component or assembly (page 32), it is unclear whether or not the various labor wage rates are weighted by the calculated number of employees in that classification to obtain a weighted average. If this has not been done, direct labor costs need to be re-evaluated. There are significant wage differentials between the various classifications with general assembler being the lowest paid. (The same applies to the indirect labor costs.)**

Question: Is the approach used in scaling the cost of power-split technology to other vehicle classes appropriate and likely to yield accurate results? Is the methodology for using the cost of power-split components in other hybrid technologies appropriate and likely to yield accurate results?

Response:

- **The use of ratios to develop sizing for HEV components such as traction motors, high traction batteries, etc. as described in the paper is appropriate and can be used effectively to estimate material costs and investment in equipment.**

- **Concerns with using the size ratio scaling methodology for certain other cost estimates is documented in other sections of the response. For convenience, they are repeated here:**
    - **Certain elements of overhead cost such as salaries and front office costs are not impacted, or at most minimally, by part size.**

    - **Direct labor costs are more closely tied to part complexity than to part size.**

- o **While part size will impact certain areas of indirect labor, such as material handlers, it will have a lesser impact on number of supervisors, quality inspectors, etc. Like direct labor, these numbers are more closely tied topart complexity than size.**

- o **The same concerns exist with establishing component costs for the P2 HEV powertrain components using manufacturing cost to component size ratios (page 127).**

- **The issues addressed above regarding scaling methodology apply equally to the P2 manufacturing cost calculations.**

Recommendations:

- **Re-evaluate the assumptions around use of a scaling factor to better define those costs which are scalable and those which are not.**

- **Assuming the validity of the approach to costing using manufacturing cost to component size ratios, provide background data supporting this assumption.**

- **As outlined above, review the application of scaling factors, especially for manufacturing cost and burden. The methodology described in the paper yields a result that should be considered as one end of a range estimate. The other end of the estimate should be developed by applying scaling factors to material cost and investment in equipment and holding the other costs constant. If it is necessary to state an absolute cost, the pick a middle ground between these two numbers based on expert opinion.**

2. **Editorial Content**

Question: Is sufficient detail provided in the body for a reader familiar with the subject report to understand the process and conclusions? Are appropriate appendices included? Please specify any specific content that you recommended be added or removed.

Response: Although a substantial amount of detail is included, there are a number of things that should be added to the report to substantiate the process and conclusions. As outlined in a number of questions above, these details are necessary to validate the processes and underlying assumptions used to arrive at the cost conclusions. These details include:

- **Validation of the Munro & Associates software including methodology and results**
- **Validation and sensitivity testing (or results of the testing) of the FEV cost algorithms**
- **Specific examples where validation testing has been done through marketplace analysis. These examples must show the FEV derived cost and the actual marketplace cost.**

- **A worked example showing the detail behind each number in the MAQS costing sheet.**
- **Sensitivity analysis for a sampling of the components and assemblies in the cost analysis.**
- **Data supporting the assumption that manufacturing costs can be calculated as a ratio of component size.**
- **Clarification of the calculations for direct labor cost.**

With the exception of the last item, all of the appropriate documentation should be provided as appendices or as links to other papers/detailed analytical data.

Question: Please comment on any editorial issues that should be addressed in the report, including any comments on general organization, pagination, or grammar and wording.

Response: The general organization of the paper is clear. The following are areas where typographical errors or other editorial issues exist:

- **Page 16—Item 2 net to the last line. "Develop" should read "Development"**
- **Page 35—next to the last paragraph references a template in Appendix E.4. This Appendix could not be found in my copy of the paper. This may just be a labeling error, but none of the pages in the appendix appeared to be the template referenced.**
- **Page 42—Next to the last paragraph, 2cnd sentence. FOB (freight on board) is usually designated as FOB, destination—supplier pays the shipping costs or FOB Factory—customer takes control of the product and pays the shipping cost. Note that in Europe, FOB is always referred to as "Free on Board". Assuming you mean the receiving company pays the freight, the more common term would be FOB Factory.**

This concludes my review.

Respectfully submitted,

Linda M. Miller

Review of Draft Report "Light Duty Technology Cost Analysis, Power Split and P2 HEV Case Studies, dated March 10th, 2011"

By

Deepa Ramaswamy, Ph.D.,

Hybrid Chakra Consulting, LLC

This report contains the review of the draft report listed above. It begins with a response to the specific charge questions from ICF. The first part of the report contains responses to the charge questions, and these are listed in Table 1 and Table 2. The next part of the report lists additional review comments in certain specific categories.

In general, FEV and Munro are to be commended for the detail that they have shown in this approach to determining hybrid system cost. The use of linked MAQS worksheets that allow the component costs to be rolled up to subsystem and system costs is a powerful tool, that can be used to do sensitivity analysis further down the line. However, the best system is only as good as the inputs/assumptions that drive it. Some of the assumptions used in this report(e.g. battery technology and size, manufacturing location, system power)that are key in determining overall system cost have to be carefully thought through and considered during future rulemaking by the EPA.

Methodology/Results:

#	Charge Question:	Reviewer Comments:
1	Is the methodology documented in the report generally reasonable and likely to yield accurate results? Is any bias likely to be introduced to the results due to methodological issues? If so, please indicate the direction of this bias and potential remedies.	The methodology for determining the costs are generally reasonable, with some significant exceptions that are listed below. • The first is the engineering development cost, which appears to have been not considered in detail in this report. An example of these are the costs to develop control systems, be they battery control systems or otherwise. They cannot be lumped in with the indirect cost multipliers (ICMs), because these costs are not borne by the OEMs. Rather, these are costs borne by the suppliers. The bias introduced by this is that the overall cost of some components is lower than it should be. The remedy for this is to revisit the engineering development costs for the subsystems. • What this report does not document sufficiently is the validation of this methodology at a subsystem or a

		system level. The bottoms up towards cost that is employed by FEV is certainly very detail oriented, but there isn't sufficient data in the report to show that the final subsystem or system costs that they result in, are inline with those developed or published by other reasonable sources.
2	Please identify any general flaws inherent in the scope of the study. Do you feel the results would be altered if the scope were more limited or expanded? Please explain.	• Although not a flaw per se, it is not clear why the 20% power and weight reduction was assumed for the P2 hybrid. This was the direction provided by the EPA to FEV, but the rationale for this is not clear, and this reviewer could not see why it is justified. • Secondly, the reports stated that the team felt that the Li Polymer battery (as opposed to NiMH) is a better long term solution for the P2 hybrid. It's unclear if this was the EPA team or the FEV team. Either way, there is no good rationale provided for such a statement, and this reviewer has not seen data (even outside of this report) to justify such a statement.
3	Are all appropriate inputs for the study being considered? Conversely, are all inputs considered in the study appropriate? Please cite any particular inputs or assumptions made by the study that you feel are inappropriate or likely to bias the results and how they could be remedied, with particular emphasis on sources of information used in determining labor rates, material prices, manufacturing burdens and other key factors.	• One of the major assumptions in this study that is flawed is that the high voltage battery will be manufactured in the United States. NiMH batteries are not manufactured in volume in the United States, and although several companies have plans to manufacture Li Ion batteries, the cells typically come from Asia. To assume that all this manufacturing is done in the US will results in artificially high unit costs for these systems. If this information is then used by the EPA for downstream rule making, it will have the effect of having hybrid technologies show up in an unfavorable light as compared to other technologies. This inaccuracy could be remedied by a modification of the assumptions in terms of where the battery will be manufactured. • This study does not present sufficient examples of independently determined system/subsystem costs to be used for validation of the costs that FEV/Munro calculates through their process. Although the report mentions this was done (section

		C.7), examples of such validation are not presented. These independently determined costs/sources should be additional inputs to this process.
4	Are the assumptions embedded in the model that affect projected cost or performance reasonable? Such assumptions might include learning curve, economies of scale, scaling parameters such as weight and power, labor rates, plant scaling, and material costs.	• In general, the assumptions that are utilized to calculate cost and performance are reasonable. One big exception (also mentioned in question 6 below) is the scaling parameter for the battery. Only two paragraphs are devoted to it in the report, and nowhere is a definition of "a common run-time", which is used in the scaling of the battery, provided.
5	Are the results expected of the study appropriate for the given scope, assumptions, and inputs? Are there other results that could be derived from the analysis that would support or contradict those cited by the study? Is appropriate validation made on the costing methodology and results? Please expand on any recommendations that you would make for analyses of study results.	• The results of the study are appropriate for the given scope, assumptions and inputs. • The description/report of the validation of the costing methodolgy is not sufficient. The report does say that experts have been consulted in determining the costs of various components, but little validation has been shown (in the report) of cost validation at a subsystem or system level. The overall costs developed by FEV would present a greater punch if there were examples of the comparison of their system/subsystem costs with other costs that have been published in literature. • FEV and Munro have the tools necessary to do a sensitivity analyses of the costs with respect to different variables of interest. Further analyses could include refinement/correction of some of the assumptions around this study (as mentioned in this review) and studying how the overall system costs are impacted by those changes.
6	Is the approach used in scaling the cost of power-split technology to other vehicle classes appropriate and likely to yield accurate results? Is the methodology for using the cost of power-split components in other hybrid technologies appropriate	• For most of the components, the approach used in scaling the cost of power split technology to other vehicle classes is reasonable and likely to yield reasonable results. The one potential exception (and it is stated as potential, because the approach is not well explained in the report) is the scaling of the high voltage battery parameters

	and likely to yield accurate results?	across the the different vehicle classes. This needs to be better explained and justified, particularly because this one component is responsible for the bulk of the cost of the hybrid powertrain. Given that the overall cost of the hybrid powertrain is so sensitive to this one component, this reviewer feels that greater care is needed in developing this cost. Conversely, there is considerable detail in the report on the costs for much more minor components, and although that is not a bad thing, the appropriate scaling of the battery system needs to have more effort put into it.

Table 1 Charge Questions – Methodology/Results

Editorial content:

Charge Question:	Reviewer Comments:
Is sufficient detail provided in the body for a reader familiar with the subject report to understand the process and conclusions? Are appropriate appendices included? Please specify any specific content that you recommended be added or removed.	In most cases, sufficient detail has been provided for a reader familiar with the subject report to understand the process and conclusions. Exceptions are: • Rationale for assuming the high voltage battery is manufactured in the United States • Development of the ED&T costs for different subsystems, particularly that for control systems • Validation of the calculated costs at a subsystem/system level • Scaling of the battery system across different vehicle classes • Cost for the high voltage DC/DC converter doesn’t appear to be included
Please comment on any editorial issues that should be addressed in the report, including any comments on general organization, pagination, or grammar and wording.	The overall report is well organized. There are a few minor typographical/grammatical issues. These are included in detail in section “Grammatical/Typographical Errors”.

Table 2 Charge Questions - Editorial Content

Additional Review Comments

The following sections provide additional review comments on the FEV report.

Battery Manufacturing

The report assumes that the battery will be manufactured in locations in North America. Although this reviewer understands this to be a constraint from the EPA, this is not a reasonable assumption. There is no large scale automotive NiMH manufacturing in North America currently and there are few plans for the same. Although there are more examples of Li Ion battery manufacturing in North America, it is questionable if Li Ion will be the battery of choice for hybrid vehicles. In this reviewer's experience/knowledge, the NiMH battery will continue to dominate the HEV market, while Li Ion will dominate the PHEV/EV market.

Applicability of the Power Split System to Vehicle Segments

The report talks about the applicability of the power split hybrid system to the sub-compact, small, large and minivan vehicle segments. It should be clarified that this group covers small SUVs, such as the Ford Hybrid Escape, which is one platform that clearly already supports this hybrid platform.

P2 Hybrid System

1. Although the EPA provided the direction to reduce the maximum system torque/power by 18-19%, the rationale for this isn't clear. Without this rationale, a meaningful comparison between the cost figures for the power split system and those for the P2 system cannot be made.
2. Why was it felt that the Li Ion battery would be more appropriate for the P2 hybrid? Li Ion batteries have much better energy density than NiMH batteries, so for applications that require large battery energy (such as PHEVs or EVs), it is understandable to use Li Ion packs. However, for the P2 application, the required kWH of the battery (from Table F-2) was less than that for the power split application (from Table E-2). Given this, the selection of the Li Ion technology for the P2 system is not well justified.

Cost Analysis Process

1. In Figure B-1, why isn't the BOM updated after step 6, when additional information has been gained about the component after its disassembly?
2. Page 50, first paragraph refers to 19,149 parts, and it wasn't clear what the 19,149 parts stand for? Are these 19,149 battery packs?
3. It isn't too clear how the engineering design costs for various components/systems have been calculated.
    a. For example, in section D.2.2, how has the engineering design cost for the Atkinson engine and the control system for it, and the calibration for it been calculated/estimated?
    b. Similarly, how is the engineering design cost for the electronics controllers, for the software for the battery system, for the mechanical design of the battery system been estimated? The actual numbers that have been presented in the tables appear to be too low.

c. In Table D-11, why is the ED&T for the traction battery assembly so high ($49) compared to that for the control module (listed as $4)? The relative engineering effort for the control module is not 12 times less than that for the design of the mechanical assembly.

System Scaling and Sizing

1. Although the scaling for the most of the components across the different vehicle classes seems reasonable, one big item that is not explained clearly is the high voltage battery. Given that it is the single most expensive subsystem within the hybrid powertrain, more care needs to be put into ensuring that this is done in a reasonable manner, and the report needs to explain how this was done. The last paragraph on page 132 talks about the “common run-time” parameter that is used to scale the battery system across vehicle segments. This parameter needs to be defined, and the report should have more of an explanation why the value of 0.0168 hours was used, and how it translates to the other parameters (power rating, energy rating) that define a battery.
2. In Table E-2, the nominal pack voltage for the subcompact passenger vehicle is quite low, namely 148V. Could other, potentially cheaper power electronics technologies be used at this battery voltage?
3. There is a small discrepancy between some of the numbers in Table E-2 as compared to those in Table D-3. For example, for the Fusion Hybrid, Table D-3 lists the net power as 142kW, whereas Table E-2 lists it as 140.6kW. Similarly, the engine power is listed as 116kW in Table D-3, but as 114.8kW in Table E-2. Even a rounding of the numbers doesn’t make them the same.

Miscellaneous

1. Table A-1 has a calculation of the percent decrease/increase in cost of adding the power split system to different vehicle segments. It would be more appropriate to calculate the percentage increase as compared to the base non-hybrid vehicle cost, instead of calculating the increase with respect to the mid/large size vehicle segement cost.
2. Nowhere in the paper (for example, section D.7.1 makes no mention of it, and neither do Tables D-5 or D-6) could this reviewer find the mention of the high voltage DC/DC converter (which converts the voltage from approx 300V to approx 600V, and subsequently utilized by the traction motor and generator), which is used in the Fusion Hybrid. The corresponding cost for this part is also not mentioned.

Grammatical/Typographical Errors

1. Page 10, 2nd line, replace “advance” with “advanced”
2. Page 11, 3rd line, replace “value” with “valve”
3. Page 18, 3rd line, replace “standardize” with “standardized”
4. Page 18, paragraph 2, 1st line, replace “very” with “vary”
5. Page 19, paragraph3, 5th line from bottom, replace “develop” with “developed”
6. Page 21, extra bullet point in Scenario #2
7. Page 52, last paragraph, replace “Too” with “To”
8. Page 52, last paragraph, replace “truck” with “trunk”
9. Page 56, 2nd paragraph, replace “approximate” with “approximately”
10. Page 91, 3rd paragraph, replace “acknowledge” with “acknowledged”
11. Page 97, 1st paragraph, replace “VEV” with “HEV”