FEV Inc. Report "Light Duty Technology Cost Analysis, Power-Split and P2 Hybrid Electric Vehicle Case Studies" – Response to Peer Reviewer Comments

United States
Environmental Protection
Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
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and

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Overview

This document provides responses to peer review comments on the FEV Report, "*Light Duty Technology Cost Analysis, Power-Split and P2 Hybrid Electric Vehicle Case Studies"* The peer review for the FEV Report was conducted by ICF International, and the documentation of their peer review process and analysis of its findings have been published in: *Peer Review of FEV Inc. Report "Light Duty Technology Cost Analysis, Power-Split and P2 Hybrid Electric Vehicle Case Studies", Final Report, March 31, 2011.*

The original text of the ICF Report is used in this document for the purpose of directly addressing each comment topic or comment theme with a response from EPA and FEV. Thus, the EPA/FEV responses are incorporated into the body of the ICF comments summary, and are identified by blue text and a response number (e.g. "***Response #:*** …) In the interest of clarity and context for the reader, the Introduction and Peer Review Process sections of the ICF Report are included in this document, but the large Appendices containing peer reviewer qualifications and the original review submittals are not.

Introduction (from ICF Report)

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

The Peer Review Process (from ICF Report)

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 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

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[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).

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.

Responses To Peer Review Comments

1. Summary of Peer Reviewer Comments

1.1. 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.

Response 1: As summarized in Report section C.7, Marketplace Validation, marketplace validation occurs at all stages of the cost analysis with special emphasis placed on cross-checking in-process costs (e.g. material costs, material selection, labor costs, manufacturing overhead costs, scrap rates, and individual component costs within an assembly).

For example, for the NiMH battery costs, over 80% of the battery component costs were validated using data from subject matter experts (SME) and/or production supplier quotes. The type of cost validation included component pricing for finished goods, raw material quotes and manufacturing equipment pricing. Both active and passive electronics components, as well as several mechanical type components including the D-cell battery canister, collectors, lid, and vent button, were all validated using industry quotes. Also the majority of the battery raw material costs (e.g. nickel-plated steel, positive and negative substrates, positive and negative powders, electrode separator) were acquired through a formal quoting process. In several instances, when prices were suspect, i.e. too low or high based on SME experience, more than one supplier quote was obtained as a means of validation. For developing the manufacturing equipment overhead rates (e.g. positive and negative coating lines, compaction lines, formation equipment), general specifications were established and sent out for quote.

This same approach was taken for many of the main high-impact components evaluated in the analysis including the traction motors, high-power electronic inverters, and high-voltage wiring. Cross-checking on final assembly costs also occurs within the scope of the cost analysis, mainly as a “big picture” check. In general cross-checking final assembly costs are typically achieved through solicitation of industry experts. For example in the case of the traction motor analysis, FEV consulted with a T1 traction motor supplier on the anticipated pricing of traction motors based on the established boundary conditions. The pricing estimate from the supplier was within 5% of the calculated value.

In response to these comments concerning the potential impact of uncertainties within the cost elements, FEV has updated the final report to include the following sensitivity analyses: 20% increase in material costs, 20% decrease in material costs, 20% decrease in manufacturing overhead rates, 20% decrease in labor rates, 20% increase in mark-up rates, 20% decrease in mark-up rates.

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.

Response 2**:** ICMs are used in EPA's rulemaking process to help determine the overall cost of a technology. The specific values assigned to the ICMs are based on the complexity of the technology. These multipliers were developed separately from this FEV costing methodology and are not used by FEV, but rather are applied by EPA to the FEV cost results. They are, therefore, beyond the scope of this Report. More information on ICMs can be found in the EPA Report 420-R-09-003. See Responses #10 and #21 for discussion of engineering development costs.

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.

Response 3: Multiple scaling methodologies were applied in the analysis based on the component type, the required change to the component for the new vehicle segment, and the data available. For example, with the traction motor (estimated 60 kW) and generator (estimated 30 kW), a ground-up cost calculation was developed for each assembly. By developing a cost/kW factor based on these two data points, costs were estimated for alternative size motors and generators.

In the scaling of the high-voltage battery, several different scaling considerations were applied. For the various vehicle segments, the battery power capacity was increased/decreased by altering the number of sub-modules (one sub-module equals 8 D-cell batteries which is approximately equal to 10.6V). In the Fusion Hybrid analysis there were 26 modules connected in series to provide 275V. To change the power capacity of the overall battery pack, sub-modules were added or deleted to suit the system requirements. As the number of sub-modules were added or subtracted from the analysis, so were the costs of the sub-modules. In addition to the sub-module costs, there were nine other sub-subsystem categories which contributed to the overall high-voltage traction battery cost. For a few of these sub-subsystem categories (e.g. Vehicle Operations assembly, body wiring harness-low voltage) the change in material, manufacturing overhead, and labor were considered insignificant so no scaling from the Fusion Hybrid calculated costs was required. With some sub-subsystem (e.g. cooling, battery covers, battery module assembly) the cost change was approximately proportional to the number of modules added or deleted. Thus a cost scaling factor was developed based on the number of modules for these types of sub-subsystems. In selected cases (e.g. traction battery sensing and control modules), where much of the hardware in the sub-subsystem remained constant regardless the number of battery sub-modules added/deleted, only the hardware changes within the sub-subsystem were accounted for, using one of two methods: (1) adding-in or subtracting-out absolute component costs, (2) applying a scaling factor against the components which would require change.

In the case of the high-voltage wire harnesses, a compensation factor was developed for each vehicle segment based on the expected change in harness length, and a cost per harness unit length. Other harness parameters would not significantly change (e.g. same connector count and performance specification, same battery current for all applications, same number of retention points). The same cost/unit length of harness used to develop the initial Fusion Hybrid model was used in the scaling portion of the analysis.

The scaling methodology for many other general components, based on an increase or decrease in size from the cost of the Fusion Hybrid components, utilized constant total manufacturing cost (TMC) and mark-up ratios to scale up or down. For example, assume the TMC cost of a Fusion Hybrid stamping was $2.50 and the breakdown in cost elements, developed from a ground-up analysis, were as follows: 50% material costs ($1.25), 10% labor costs ($0.25), and 40% in manufacturing overhead costs ($1.00). If the stamping doubled in size (i.e., mass), maintaining the same TMC ratios, the material cost would go to $2.50, labor costs to $0.50, and manufacturing overhead costs to $2.00. The manufacturing overhead increase is rationalized by a larger press and longer cycle time where as the added labor cost is the resultant of a longer cycle time.

In cases such as battery assembly, FEV and EPA agree that labor and manufacturing overhead are not ratiometric to material mass/size changes. In these cases the methodology did employ custom scaling factors for labor and manufacturing overhead based on input from subject matter experts. FEV has added a sensitivity analysis in response to this comment.

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).

***Response 4*:** We agree that extension of the analysis to other hybrid architectures may be useful, but this is beyond the scope of the work assignment and tasks assigned by EPA to FEV. See also Response #9.

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.

***Response 5*:** Scaling was done on two levels in this analysis. First, component costs from the powersplit hybrid large car (Fusion) were scaled to get costs for same or similar components on vehicles of the same size but using a P2 hybrid design. Second, both powersplit and P2 hybrid costs for the large car category were scaled to other vehicle sizes. We agree that there is potentially greater uncertainty in the cost estimates as they move further away from direct reliance on teardowns and toward more reliance on scaled results. However, cost and time constraints, and the lack of production P2 hardware at the time the work was initiated, made it unworkable to conduct more teardowns and thereby reduce the need for scaling. The scaling parameters and methodology were carefully developed to avoid reliance on subjective or arbitrary assumptions, and to ensure high confidence in the whole range of results. Specific comments about scaling for P2 components and across vehicle sizes are addressed in Responses #3, #7, and #9; we have also added sensitivity analyses to the Report to help address these comments.

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.

Response 6**:** See Response #2.

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 powersplit 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.

Response 7**:** We did not assume significant all electric range (AER) capability in the P2 hybrid being costed and so did not evaluate the ability of the electric motor and associated components to provide required torque and power for AER. We have revised the Report to note this so that users of the Report results may be aware of it.

Since we were not considering significant all electric driving modes for the P2 application, we believe motor sizing based on power is correct for this analysis. Furthermore, EPA engineers involved with this project have evaluated the P2 designs now nearing production to help validate our choices of machine specifications and found good correlation. The Report has been clarified regarding how weight reduction is factored-in to the P2 architecture. Note that the mass reductions considered in the P2 analysis are the result of non-hybrid-specific innovations, such as the shift to lighter materials throughout the vehicle.

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.

***Response 8*:** The Report has been revised to clarify the basis for the 20% weight reduction (and resulting reduction in required power), and for the costing of a Lithium-polymer battery in the P2 vehicle but not the powersplit vehicle. It is not the migration from powersplit to P2 architecture that enables these changes; we think it likely that the powersplit hybrid could incorporate the weight reduction and use of Lithium-polymer battery as readily as the P2 hybrid, though this was not evaluated. Rather, the weight reduction was specified by EPA as an upfront assumption for the FEV analysis, and was for technology innovations not related to hybridization such as a shift to lighter materials throughout the vehicle; it included consideration by EPA of offsetting weight additions from hybridization.

Likewise the Report included a Lithium-polymer battery for the P2 architecture and a NiMH battery for the powersplit architecture not because these are inherently the right choice for these two types of HEVs, but because the EPA team expects Lithium-polymer batteries to have great potential for use in hybrids and asked that it be included in the P2 costing. On the other hand, for the powersplit costing, EPA directed FEV to maintain the Fusion characteristics (weight and battery type) in order to keep that result focused on the teardown findings, with minimal extrapolation to other hardware that might sensibly find its way into later-generation hybrids, such as Li-polymer batteries and lightweight materials. For this reason, it would not be appropriate to compare the powersplit and P2 cost results on an equivalent basis.

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.

***Response 9*:** We agree that extending the Report's findings to vehicle types or hybrid architectures not specifically covered in the Report should not be undertaken without a properly crafted methodology for doing so, although, depending on how far the extension goes, we do not think it would necessarily require extensive new teardowns. See Responses #3, 5 and 7 for additional responses on the scaling issues raised by these peer reviewers.

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.

***Response 10*:** At the OEM level, all 3 of these concerns are accounted for by applying an Indirect Cost Multiplier (ICM), to the FEV results (see Response #2). At the supplier level, the cost of developing control software, integrating the electrical/mechanical parts, and calibration are accounted for with an ED&T cost for each component, which is a percentage of the component cost, based on its complexity, in the context of the methodology assumptions and in particular in the assumption of high volume production.

Ms. Miller was concerned that lack of communication [i.e. independent review of the study] 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.

Response 11**:** The Agency does not typically ask the party that is potentially being regulated for direct review of cost assumptions prior to publication of a rulemaking analysis. However OEMs can and do provide extensive review of EPA cost analyses through the public process required in every rulemaking. We have high confidence in the study validation methodology because the subject matter experts (SMEs) utilized by FEV in the validation process are familiar with OEM manufacturing practices and cost structures, and their input improves the veracity of FEV final cost results. See also Response #1 for discussion of the extensive marketplace validation performed by SMEs.

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.

Response 12**:** The assumption of U.S.-based manufacturing was directed by EPA and is typical of FEV's cost analyses for light-duty vehicle rules, based on direction from EPA. We agree that some elements of vehicle component production are likely to occur elsewhere, and, because this would most likely be for the purpose of cutting costs, the assumption serves to make FEV's analysis conservative (i.e., biased toward higher costs). However, we believe trends toward greater alignment of global wage structures and rising costs of long-distance shipping will tend to mitigate this impact in the future. Furthermore this approach ensures a consistent framework for costing performed by FEV as part of this work assignment.

We note that the question of future production locations for vehicle batteries and subcomponents is far from settled. HEV systems represent a relatively new manufacturing sector and the ultimate location of production facilities is yet to be determined for the domestic market. Sizable new investments in the United States have been initiated within the past few years. See also Response #14e.

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.

Response 13**:** All of the underlying information in the FEV cost analyses (including databases, spreadsheet formulas, and process flow diagrams) are available to the public via the rulemaking docket. Any component supplier or OEM should be able to work with this information, and understand exactly how the costs were determined. If suppliers, OEMs, or other stakeholders discover any errors or incorrect assumptions in the FEV analysis, we encourage them to notify EPA. The FEV methodology is not intended to be used by others as a standalone model. We agree that people with expertise in this type of analysis would be needed to build on the FEV analyses. See Response #3 regarding battery scaling assumptions.

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.
    - ***Response 14a*:** When conducting the cost analysis for each technology configuration, a number of assumptions and boundary conditions are required upfront in the analysis prior to the start of any costing work. The same assumptions and boundary conditions are applied to both the new and baseline technology configurations, establishing a consistent framework for all costing and resulting in a level playing field for comparison. The user of the FEV cost estimate must be aware of these boundary conditions when determining if the FEV cost estimate is applicable to the user's specific situation.
    - To account for cost differences arising from factors outside of this framework, such as differing technology maturity levels in the timeframe of interest, EPA may decide to apply adjustments, such as reverse learning factors.
    - ED&T expenses are coved at the supplier manufacturing level within the mark-up rate applied by FEV. ED&T at the OEM level is applied through the application of an Indirect Cost Multiplier (ICM). See Responses #2, #10, and #21.
    - Capital costs are included in the manufacturing overhead rate based on a straight-line depreciation method with zero end-of-life value.
- 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.
    - ***Response 14b*:** Within the manufacturing overhead rate/burden rate calculator template, which calculates the overhead rates for various operations and processes, there are allowances made for equipment "maintenance, repair and other" (MRO) expenses. The contributions are calculated as a percentage of the primary and process support equipment costs. The Report has been revised to clarify this point.
- 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.
    - ***Response 14c*:** The matching of new technology with timing of product cycles is not within the scope of this study. However it is a key facet of the methodology

used by EPA to ensure that new technology introduction due to standards does not disrupt manufacturers' product cycles. This is accomplished through the assumption of technology phase-in caps and specified product cycle intervals in the agency modeling work.

- 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.
  - ***Response 14d*:** Tolerance limits are considered to be one of the parameters defining part complexity, which in turn affects costs. Through SME reviews, which consider many variables including tolerance and performance requirements, scrap rates are set accordingly. For example compressor wheels in turbochargers have tight tolerance requirements and therefore were assigned a higher scrap allowance in the FEV Pilot Study and additional case studies. In addition, the cost of manufacturing tight-tolerance parts is accounted for in manufacturing equipment selection and cycle times.
- The assumption that all sourcing/manufacturing centers will be in the United States was not valid and could bias the results high or low.
  - ***Response 14e*:** See Response #12. To establish a consistent framework for costing, a common cost structure was required for all cost analyses. This included establishing a common manufacturing location, the United States. Based on this boundary condition, most manufacturing operations and processes were developed under the assumption of heavy automation with less manual labor. This key assumption was directed by EPA at the start of this cost analysis and, to the extent that it might bias the costs, it will do so in a conservative direction, i.e., somewhat higher costs. Recent trends in manufacturing dynamics for advanced technology components make it difficult to predict the degree and direction of low-cost-country sourcing. We believe that trends toward greater alignment of global wage structures and rising costs of long-distance shipping will tend to mitigate this impact in the future.
- 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 expenses.
  - ***Response 14f:*** Labor rates do include allowances for overtime costs and other shift premiums. These allowances are applied to the base wages as part of the fringe calculation. Note that the rulemaking assumption that rollout of the new technologies as a result of the standards will not disrupt the normal production practices employed by OEMs and suppliers, helps to mitigate any need to assume excessively large additional allocations for overtime pay. (See Response #14c).
- Packaging cost assumptions should be checked, based on the sample calculation (page 50, Figure C-6).
  - ***Response 14g*:** FEV has made some simplifying assumptions in calculating packaging costs because these costs are a very small part of the overall new

technology costs. We believe a more thorough analysis of packaging costs would not have a significant effect on the overall cost numbers.

- Allowances for a percentage of pallets/racks out for cleaning/repair are not included and biased the packaging cost low.
  - ***Response 14h*****:** The cost analysis includes a cost allowance in the manufacturing overhead rate for general plant and dunnage cleaning. The Report has been revised to clarify this point.
- 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.
  - ***Response 14i*****:** At the assumed 450K annual volume for hybrid technology components, subsystem, and systems, it is expected that the technologies costed are all produced on dedicated lines. In addition, given the high-volume/mature-technology assumption, an 85% utilization is justified. If manufacturers do in fact decide to mix other technologies into these lines, we would expect the reason for doing so would be to reduce overall costs in comparison to building on two lines, and so would not warrant assigning a cost increase to the high-volume technologies covered in the report.
- 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.
  - ***Response 14j*****:** See Response #3.

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.

Response 15**:** An objective of the technology cost analysis associated with the EPA rulemaking effort is to generally assume equivalent performance (other than fuel economy) between baseline and new technology configurations. For example, cost analysis that assumes significantly reduced acceleration in new technology vehicles would not be expected to adequately inform EPA rulemaking decisions, because of the added complexity it would introduce over customer acceptance and safety. Similarly, because towing capability is essential for large trucks, we assumed that downsizing of the engine would not be appropriate for these vehicles. The blending and depth of discharge characteristics were selected by EPA, consistent with the equivalent performance objective, as inputs to the study's P2 component sizing determinations.

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.

***Response 16*: ** See Responses #1, #3, and #11. FEV is adding sensitivity analyses to the Report in response to the peer review comments.

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.

***Response 17*: ** See Responses #3, #5, and #7.

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.

***Response 18*:** Consistent with the core philosophy for all of the cost work performed by FEV for EPA, we chose to determine Li-ion battery costs based on teardown of an actual production battery. We agree that other configurations exist or may exist in the future, but these will likely only serve to lower eventual battery costs to the extent that they prove more cost effective than the design we chose, thus making the battery costs developed by FEV somewhat on the conservative side. Li-ion battery sizes for the vehicle segments analyzed were provided by the EPA team as an input to the P2 HEV cost analysis; depth of discharge constraints to ensure a robust battery life was one of the considerations taken into account by the team. The battery sizes costed for the P2 vehicle analysis are provided in Table H-2 of the Report. See Response #3 for additional discussion on how the scaling of battery costs across the vehicle segments was carried out.

1.2. 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 powersplit 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.

***Response 19*:** The applicability of the powersplit hybrid system technology to the various vehicle segments was established by EPA as part of the study inputs and so is within the scope of the broader rulemaking analysis rather than the FEV Report. Note that the Ford Escape falls into the large car segment, and therefore actually is included in the powersplit cost analysis.

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.

***Response 20*:** The DC/DC converter was included in the analysis and covered in the Report in section D.7.1.2 “Voltage Converter/Inverter Subsystem”. The costs of the DC-DC converter were reported in Table D-10.

The discrepancies between Table D-3 and Table E-2 (now labeled “F-2” in the Final Report) are based on the using an electric horsepower to kW conversion (0.746) versus mechanical horsepower to kW conversion (0.736).

The comparison bill of materials (C-BOM) referred to in Figure B-1 is a top level BOM used to identify component/assembly differences at a high level. Every component or assembly which is disassembled further for a cost analysis has a separate manufacturing indented BOM.

In the packaging calculator section of the Report, the 19,149 identifies the estimated number of battery packs which would be shipped out in a two-week window. This number is directly used to calculate the dunnage costs.

The percent increase in cost for each vehicle category (Table A-1) over the baseline vehicle is not included in this study because we did not cost the base vehicle in each category.

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).

***Response 21*:** Within the automotive industry, there are several methods used to calculate ED&T. These methods range from a detailed build-up of estimated R&D and ED&T costs (at all levels, Tier 1, Tier 2, Tier 3), which are then amortized over a defined annual volume and life cycle, to a percent allocation, based on component complexity, of the total manufacturing costs. In between these two methods are hybrid approaches which utilize a combination of the two methods. The exact method an OE or supplier may choose to use, or accept, may be based on several factors including size of company, product portfolio, production volumes, product range (i.e., custom, commodity or hybrid of the two), market risk, dual sourcing, and product experience.

Performing a comprehensive work-up of ED&T costs, for every component, appears on the surface to be the most robust method. However the probability of accomplishing this task accurately, based on the amount of detailed information required, without the necessary confidential business information, is very low.

For the EPA cost analyses, FEV chose to use the percent allocation of total manufacturing costs as the method for calculating ED&T costs. This same methodology is used extensively by automotive suppliers and OEs in today's industry. Also this is the same method chosen by FEV, for all costing work, conducted for all customers.

FEV's ED&T rates are based on a constant recovery/payback rate. This constant rate is based on the assumptions that the established automotive supplier, within a stable economy, will maintain a certain size R&D department, product and design engineering department, and test department. The cost to run this department will generally remain proportional to the value of manufactured product leaving the facility, under a stable business climate. There are always exceptions to these rules. For example, where the integration of the new technology configuration is slow to reach financial planning volumes, or an existing technology remains in production for an extended life, with no replacement technology planned, adjustments to rates should be applied – based on the defined boundary conditions.

Based on the assumptions and boundary conditions established for the EPA cost analysis project (i.e., well developed product designs, high production volumes, high first time manufacturing yields, significant marketplace competition, low field warranty, etc) an ED&T

mark-up range between 0% to 6% has been selected for the analysis. The selected range is based on a combination of publications from OEMs and suppliers, input from FEV's subject matter experts in manufacturing, examining ED&T mark-up rates in the automotive industry, publicly-available financial data (i.e., 10K reports), and EPA's Indirect Cost Multiplier report.

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.

***Response 22*:** See Responses #1 and #11. We agree that it may be instructive to compare costs of hybrid components from this study with those from other studies that focus on other hybrid and electric vehicle designs. However, we believe these vehicles are markedly different in function and design and so such comparison would not directly inform the validity of the FEV study results.

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.

***Response 23*:** As discussed in Response #1, cost validation occurs at multiple stages of the analysis. During the build-up of cost models, much of the information acquired to construct the models is based on supplier quotes. In general, subject matter experts (SMEs) construct all cost models. Once the cost models are completed, the SME will review the models for accuracy by running some pilot runs with components/assemblies with known costs as part of the validation process.

Information loaded into the databases comes from various reputable sources. For example the majority of high impact material pricing comes from supplier quotes. The data contained within the labor databases is extracted from the Bureau of Labor Statistics. We have added sensitivity analyses to the Report in response to the peer review comments.