Title

AVCEM DOCUMENTATION PART 3: REVIEW OF THE LITERATURE ON THE PRIVATE AND SOCIAL LIFETIME COST OF ELECTRIC AND ALTERNATIVE-FUEL VEHICLE COSTS

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AVCEM: ADVANCED-VEHICLE COST AND ENERGY-USE MODEL

AVCEM DOCUMENTATION PART 3: REVIEW OF THE LITERATURE ON THE PRIVATE AND SOCIAL LIFETIME COST OF ELECTRIC AND ALTERNATIVE-FUEL VEHICLE COSTS

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AVCEM DOCUMENTATION REPORTS

1) AVCEM Documentation Part 1: Overview of AVCEM
2) AVCEM Documentation Part 2: General Concepts and Methods
3) AVCEM Documentation Part 3: Review of the Literature on the Private and Social Lifetime Cost of Electric and Alternative-Fuel Vehicles
4) AVCEM Documentation Part 4: Cost-Year Basis, Consumer Interest Rates, Inflation, and other Financial Parameters
5) AVCEM Documentation Part 5: Baseline Vehicle Manufacturing Cost, Weight, and Lifetime
6) AVCEM Documentation Part 6: From Variable Manufacturing Cost to Retail Cost
7) AVCEM Documentation Part 7: Vehicle Energy Use and Performance
8) AVCEM Documentation Part 8: Energy Use of Internal-Combustion Engines
9) AVCEM Documentation Part 9: Electric and Alternative-Fuel Powertrain Performance, Cost, and Lifetime
10) AVCEM Documentation Part 10: Battery Performance, Cost, and Lifetime
11) AVCEM Documentation Part 11: Fuel-Cell and Hydrogen-Storage System Performance, Cost, and Lifetime
12) AVCEM Documentation Part 12: Periodic Ownership and Operating Costs
13) AVCEM Documentation Part 13: Energy Feedstock, Production and Delivery Costs
14) AVCEM Documentation Part 14: External Costs and Non-Cost Transfer Payments
15) AVCEM Documentation Part 15: Results from AVCEM
16) AVCEM Documentation Part 16: References and Parameters

We revise the documentation reports periodically. The most current versions of the documentation reports are published on Delucchi's faculty web page, www.madelucchi.berkeley.edu. Archived versions are at http://escholarship.org.

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REVIEW OF THE LITERATURE ON THE PRIVATE AND SOCIAL LIFETIME COST OF ELECTRIC AND ALTERNATIVE-FUEL VEHICLES

INTRODUCTION

Objectives

In order to assess the state of knowledge of the private and social lifetime cost (LC) of conventional and alternative-powertrain vehicles (mainly electric vehicles), we reviewed and evaluated 190 LC studies published between 2000 and 2020. (We also sometimes refer to lifetime cost as the "total cost of ownership," or TCO.) Our main objective was to determine which aspects of the LC of motor vehicles were well researched and well analyzed, and which aspects were less well researched and analyzed and accordingly would benefit most from a focused new research effort. In some cases, data sources, results, and methods from the literature informed the development of our own models and estimates of components of the private and social LC.[1]

Template used to evaluate the literature

We used a template, shown as Table 1, to evaluate the rigor and level of detail of the LC studies we reviewed. The template lists the main elements in a LC analysis. For each study, we evaluated the quality of each LC element and, in some cases, summarized or commented on the results or methods.

In order to have a consistent evaluation of the LC elements across the studies, we created standardized quality ratings, which are explained in Table 2. Notes and abbreviations used in the template are shown with the Table 1 template.

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[1] Some of this material appears in:

A. Burnham, D. Gohlke, L. Rush, T. Stephens, J. Zhou, M. A. Delucchi, A. Birky, C. Hunter, Z.g Lin, S. Ou, F. Xie, C. Proctor, S. Wiryadinata, and N. Liu, *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains*, draft report for the US Department of Energy, Argonne National Laboratory, February (2021).

Findings

As mentioned above, we reviewed 190 studies published within the last 20 years. About 36 of the studies estimated the LC of medium-duty (MD) or heavy-duty (HD) vehicles (including buses); the remainder estimated the LC of light-duty (LD) vehicles. (See Hewlett, 2020, for a recent review of a few of the MD and studies reviewed here.) The vast majority of the studies were journal articles, relatively short reports, or sections of larger reports. However, as discussed next, only a handful were comprehensive and detailed.

Table 3 summarizes the quality ratings from the review templates. In general, few studies are *comprehensive* (cover all components of the LC), *original* (as opposed to reliant on other work), and *detailed (*as opposed to being based on simple assumptions). For example, as shown in Table 3, only about 6% of all of the individual estimates, for all studies and all cost elements, are original and detailed (A1 or A2 rating), and only 10 studies – about 5% of the total – have at least 3 detailed estimates (either A1 or A1* rating) (Table 4a). (The studies with at least 3 detailed and documented estimates are discussed in the next major section.) Many studies omit cost elements or make simple assumptions with little or no original analysis. And few if any studies develop a proper conceptual framework for estimating the LC.

In particular, we found only three studies that included an original, detailed estimate of non-energy operating costs such as insurance and maintenance and repair: the comprehensive cost model of Delucchi and Lipman (2001), a detailed regulatory analysis by EPA (2009), and the review of original survey data by Harto (2020). These studies are discussed more below.

Table 4a lists studies with 3 or more ratings of A1 or A1*. Table 4b presents studies with an A1 rating for each cost element.

A spreadsheet accompanying this report evaluates all of the studies according to the template shown as Table 1, with the quality ratings described in Table 2. The remainder of this report provides further discussion of the best studies, which include detailed work by the Federal Government for Regulatory Impact Analyses, and earlier work by Delucchi and others.

As expected, the review supports the need for a more rigorous, comprehensive, detailed, up-to-date, internally consistent, transparent private and social LC study. Table 5 summarizes the research needs based on our review of the literature.

TABLE 1. TEMPLATE USED TO EVALUATE THE LITERATURE

Item	Comment on how to use the item
Study name (author, date)	
Vehicle technologies and fuels	See notes to this table.
Vehicle classes	See notes to this table.
Costs estimated	See notes to this table.
Target years	The year the analysis is targeted to.
Year of dollars	
Production volumes	
Quality of estimate of cost of major new components	Battery, fuel cell, electric powertrain, H2 storage ($/kWh, and/or $/kW).
Quality of estimate of vehicle manufacturing cost	Can include estimates of material costs, labor and assembly costs, and other variable overhead costs. Excludes new powertrain components, which are covered separately.
Quality of estimate of vehicle retail cost	Equal to variable manufacturing cost plus fixed division and corporate costs, dealer costs, transportation costs, and taxes and fees.
Quality of estimate of energy use	Energy use in BTU/mile can be estimated in absolute terms, or relative to gasoline vehicle.
Quality of estimate of price of energy	Includes energy production, delivery, refueling, station. Includes EV charging and H2 refueling infrastructure.
Quality of estimates of non-energy operating costs	Insurance, maintenance and repair, vehicle registration, tires, oil and fluids, inspection, accessories.
Quality of estimates of external costs (in physical units)	For example, grams-pollution/mi-travel; gal-oil use/mi-travel. See notes to this table.

TABLE 1 CONTINUED.

Quality of estimates of external costs (in dollars)	For example, $/gram-pollution; $/gal-oil use. See notes to this table.
Quality of estimates of other factors affecting lifetime cost	Includes vehicle and component lifetime; interest rates and other financial parameters; depreciation or resale value; mileage schedule.
Assumed or estimated price of energy (fuel or electricity)	For example, $/gal or $/kWh including taxes
Sample lifetime-cost result (e.g., cost per mile, breakeven gasoline price)	Generally shown for the CLC (consumer lifetime cost) or SLC (social lifetime cost). See below for list of reported metrics.
PHEV utility factor	Fraction of miles on electricity rather than gas.
Citation and URL (if available)	
General comments	

n.e. = not estimated; n.m. = not mentioned

Notes to Table 1.

Vehicle technologies and fuels	**Vehicle classes**
ICEV = internal combustion-engine vehicle	MC = micro-car
BPEV = battery-electric vehicle	SC = subcompact LDV
FCEV = fuel-cell electric vehicle	C = compact LDV
PHEV = plug-in hybrid electric vehicle	MS = mid-size LDV
HEV = hybrid electric vehicle	FS = full-size LDV
H2 = hydrogen	LDT = light-duty truck
MeOH = methanol	MDT = medium-duty truck
BIO = biofuel	HDT = heavy-duty truck
NG = natural gas	SUV = sport-utility vehicle
G = gasoline	LDV = light-duty vehicle
D = diesel fuel	HDV = heavy-duty vehicle

Costs estimated

MC = manufacturing cost ($): the total cost of all variable labor and materials in a complete vehicle (excludes fixed costs, overhead, profit, etc.)

RC = retail cost ($): the grand total retail-level cost of the whole vehicle, estimated either directly as such, or as MC + the non-variable costs that constitute the rest of the RC

IMC = incremental manufacturing cost ($): the *difference* between the MC of the alternative-powertrain vehicle (APV) and the MC of the baseline vehicle

IRC = incremental retail cost ($): same as IMC but based on the RC

FC = fuel-use (energy-use) costs (usually $/mile; typically calculated as FCG/FE)

MR = maintenance and repair costs ($/mile)

INS = insurance costs ($/mile)

OOC = other operating costs besides FC, MR, and INS ($/mile (e.g., registration)

EC = external costs ($/mile): air-pollution, climate-change, noise, and oil-use

CLC = consumer lifetime costs ($/mile) (in the literature this generally is an estimate of the “total” lifetime cost to the consumer, expressed in $/mile, and usually includes at least energy cost and retail cost, but also can include other non-energy operating costs and component replacement costs)

SLC = social lifetime costs ($/mile) (in the literature this usually is estimated as the CLC plus some external costs, typically air pollution and/or climate change)

TCM_{APV} = total cost per mile of APV ($/mile)

TCM_{CV} = total cost per mile of baseline conventional (petroleum-fuel) vehicle ($/mile)

FCG = fuel cost per gallon (or gasoline-gallon equivalent) ($/gal)

FE = fuel economy (mi/gal)

BEP = break-even petroleum-fuel price ($/gal) = $(TCM_{APV} - TCM_{CV}^{*}) \cdot FE$

$TCM_{CV}^{*} = TCM_{CV} - FC_{CV}$

External costs and related

P = air pollution

GHG = greenhouse-gases

OU = oil use

N = noise

NCT = non-cost transfers

TABLE 2. QUALITY OF ESTIMATES

Rating	Explanation of quality rating
A1	A comprehensive, detailed and original analysis or model, with complete documentation (e.g., a study that features original models of manufacturing cost, energy use, air pollution damages, or emissions).
A1*	Same as A1, but based on use of models developed by others (e.g., a study that uses the GREET (Green House Gases, Regulated Emissions, and Energy use in Transportation) model to estimate life-cycle emissions, BatPac (ANL, 2021c) to estimate battery manufacturing cost), or Autonomie to estimate vehicle energy use and manufacturing cost.
A2	Similar to A1 – an original analysis – but significantly less detailed and comprehensive.
B	Estimate based on a very simple calculation or function. Whereas A1 studies have detailed models, and A2 studies have several functions, B studies have only a single calculation or function.
C	Estimate based on review and analysis of the literature, without any original calculations or modeling of any kind.
D	Assumption based on a literature citation with no analysis or review of the literature, or no citation at all.
n.e.	not estimated.

TABLE 3. SUMMARY OF QUALITY RATINGS FOR THE LITERATURE REVIEWED

Cost aspect	**Number of studies with quality rating of:**						
	A1	*A1**	*A2*	*B*	*C*	*D*	*n.e.*
Major new components	12	15	11	15	58	1	78
Vehicle manufacturing cost	5	10	6	5	26	3	135
Vehicle retail cost	2	8	5	10	41	3	121
Energy use	13	16	7	15	33	9	97
Energy price	2	7	5	11	45	9	111
Non-energy operating costs*	2	6	3	4	25	5	145
External costs (in physical units)	8	23	12	6	21	1	119
External costs (in dollars)	1	7	2	2	14	0	164
Other factors affecting lifetime cost	1	2	6	8	25	4	144
Total	**46**	**94**	**57**	**76**	**288**	**35**	**1114**
% of total ratings (1710)	**2.7%**	**5.5%**	**3.3%**	**4.4%**	**16.8%**	**2.0%**	**65.1%**

Notes: n.e. = not estimated.

*Insurance, maintenance and repair, and other costs such as tolls and fees

TABLE 4A. STUDIES WITH 3 OR MORE RATINGS OF A1 OR A1*

Study	**Year**
Delucchi and Lipman	2001
Electric Power Research Institute (EPRI)	2001
Lipman and Delucchi	2006
Goedecke et al.	2007
U.S. Environmental Protection Agency (EPA)	2009
Sun et al.	2010
National Research Council (NRC)	2013
Stephens et al.	2016
Lee and Thomas	2017

TABLE 4B. STUDIES WITH A1 RATING FOR EACH COST ITEM

Cost element	Study with rating of A1
Cost of major new components	Delucchi and Lipman, 2001; Tsuchiya and Kobayashi, 2004; Carlson et al., 2005; James and Kalinoski, 2007; Lasher et al., 2007; EPA, 2009; Sinha, 2009; James et al., 2010; EPA, 2011; James et al., 2011; NRC, 2013; Posada et al., 2016
Vehicle manufacturing cost	Delucchi and Lipman, 2001; EPA, 2009; Moawad et al., 2016; Vijayagopal et al., 2019; Islam et al., 2020
Vehicle retail cost	Delucchi and Lipman, 2001; EPA, 2009
Energy use	Delucchi and Lipman, 2001; Elgowainy et al., 2010; EPA and NHTSA, 2011; NRC, 2013; Zhao et al., 2013; Brooker et al., 2015; Rousseau et al., 2015; Moawad et al., 2016; Xu et al., 2018; Giordano et al., 2018; Vijayagopal et al., 2019; Hamza et al., 2020; Islam et al., 2020
Price of energy	Camus and Farias, 2012; Zhang et al., 2013
Non-energy operating costs	Delucchi and Lipman, 2001; EPA, 2009
External costs (in physical units)	Elgowainy et al., 2010; EPA, 2010; EPA and NHTSA, 2011; Camus and Farias, 2012; EPA, 2012; NRC, 2013; Torchio and Santarelli, 2010; Giordano et al., 2018
External costs (in dollars)	EPA, 2010
Other factors affecting lifetime cost	Brooker et al., 2015

TABLE 5. DISCUSSION OF RESEARCH NEEDS

Cost element	Research need	Discussion
Major new components	Modest	Detailed models of costs of batteries and fuel cells are available for LDVs and have been used in or developed for LC studies (Table 3 and Table 4b), but need to be extended to HDVs. More work is needed to develop cost data and models for electric powertrains and for gaseous fuel tanks, for LDVs and HDVs.
Vehicle manufacturing cost	Significant	Relatively little original work has been done on estimating manufacturing cost and retail cost, apart from modeling the cost of new components. More work is needed on cost of new materials for gliders, body, etc.
Vehicle retail cost		
Energy use	None/minor	Detailed energy-use models for conventional and electric-powertrain vehicles are available and have been used in or developed for LC studies (Table 3 and Table 4b).
Energy price	Minor/modest	Very few LC studies have developed original estimates of energy price, but detailed energy-price estimates and projections are available from the Energy Information Administration and other organizations. More work is needed on the cost EV charging infrastructure.
Non-energy operating costs	Significant, especially for insurance, m&r	Very few studies have made original, detailed estimates of the main non-energy operating costs, insurance and maintenance and repair (Table 2 and Table 4b).
External costs (in physical units)	Minor/modest	A few LC studies have developed original estimates of emissions of pollutants or greenhouse gases, but many have used detailed models developed by others (Table 3).

TABLE 5, CONTINUED.

External costs (in dollars)	Modest	Very few LC studies have developed original estimates of external costs, but some studies have used detailed models developed by others (Table 3 and Table 4b).
Other factors	Significant, especially for depreciation	Very few studies have developed or used detailed estimates of other factors affecting lifetime costs.

Notes: m&r = maintenance and repair.

DISCUSSION OF MOST DETAILED, ORIGINAL, COMPREHENSIVE STUDIES

Studies from oldest to most recent.

Delucchi and Lipman (2001)
cost of major new components – A1
vehicle manufacturing cost – A1
vehicle retail cost – A1
energy use – A1
non-energy operating costs – A1
*external costs (physical units) – A1**
*external costs (in dollars) – A1**

Delucchi and Lipman develop a detailed, integrated model of the performance, energy use, manufacturing cost, retail cost, and lifecycle cost of electric vehicles and comparable gasoline internal-combustion engine vehicles (ICEVs). The integrated model has three major parts: a sub-model of vehicle cost and weight; a sub-model of vehicle energy use; and an assessment of periodic ownership and operating costs. The sub-model of vehicle cost and weight consists of a model of manufacturing cost and weight, and a model of all of the other costs – division costs, corporate costs, and dealer costs – that compose the total retail cost of a vehicle. The manufacturing cost is the materials and labor cost of making the vehicle, estimated for each of the nearly 40 sub-systems that make up a complete vehicle. This sub-model also performs detailed analyses of the manufacturing cost of batteries and electric drivetrains.

The lifecycle cost aspect of the model handles insurance payments in some detail. It establishes a relationship between the liability and physical-damage insurance premiums, and the value and annual travel of a vehicle. The maintenance and repair cost analysis is based mainly on the comprehensive data on sales of motor-vehicle services and parts reported by the Bureau of the Census

Delucchi and Lipman find that in order for electric vehicles to be cost-competitive with gasoline ICEVs, batteries must have a lower manufacturing cost, and a longer life, than the best lithium-ion and nickel±metal hydride batteries projected at the time.

EPRI (2001)
*cost of major new components – A1**
*vehicle manufacturing cost – A1**
*vehicle retail cost – A1**
*energy use – A1**
*external costs (in physical units) – A1**

The Electric Power Research Institute (EPRI, 2001) uses two methods to estimate vehicle RPEs (Retail Price Equivalents). In the first method, adopted as the "Base Method" by the Hybrid Electric Vehicle Working Group (WG), component costs are estimated as the cost of labor and materials for each component. In the second method, developed by Argonne National Laboratory (ANL) with the input from WG, component costs are estimated to be what a manufacturer would pay to build the component itself or buy it from a supplier.

To estimate the manufacturing cost, EPRI uses Component-Based Cost Analysis. This method estimates glider costs, engine costs, transmission costs, electric traction costs, accessory costs, storage system costs, battery module cost, other battery component costs and charger costs.

Operating costs, including costs for fuel and maintenance, are calculated using label-adjusted fuel economies and representative driving patterns based on survey results.

To estimate emissions, they use the NREL (National Renewable Energy Laboratory) ADVISOR (Advanced Vehicle Simulator) model (NREL, 2021), the ANL GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model, and data from the California Air Resources Board. ADVISOR models the performance of conventional vehicles, electric vehicles, and hybrid vehicles. GREET estimates the lifecycle energy use and GHG emissions associated with various transportation pathways (ANL, 2021b; Wang, 2001).

The base (WG) method and the ANL method are summarized in Table 6.

TABLE 6: SUMMARY OF THE BASE AND ANL METHODS IN EPRI (2001).

Item	Base Method	ANL Method
Component Costs	Assumes all costs are manufacturer costs for labor and materials.	Same cost as Base Method, except it assumes that motor , controller and batteries already have a partial mark-up from supplier.
Manufacturer Mark-up	All component costs except batter y modules are marked-up at 1.5 times component cost.	All components manufactured by the vehicle manufacturer are marked-up at 2 times component costs, those purchased from an outside vendor are marked-up at 1.5 times component costs.
Battery Module Mark-up	Battery module mark- ups are fixed at: -- \$800 for the HEV 0 battery -- \$850 for the HEV 20 battery -- \$900 for the HEV 60 battery.	Same as Base Method.
Dealer Mark-up	All components carry an additional mark-up of 16.3% of manufacturer marked-up prices.	Included in manufacturer mark-up.
Development costs	Development costs for 2010 component technology (amortized over 5 years of production) are added at: -- \$94 per vehicle for the CV -- \$440 for the HEV 0 -- \$464 for the HEV 20 and HEV 60.	Included in manufacturer mark-up.

Lipman and Delucchi (2006)
*cost of major new components – A1**
*vehicle manufacturing cost – A1**
*vehicle retail cost – A1**
*energy use – A1**
*non-energy operating costs – A1**
*external costs (physical units) – A1**
*external costs (in dollars) – A1**

This paper analyzes the manufacturing costs, retail prices, and lifecycle costs of five hybrid gasoline-electric vehicle types in high-volume production. Updating and major modifications are made to a detailed motor vehicle retail and life- cycle cost spreadsheet model that had previously been used to analyze the costs of conventional vehicles, electric-drive vehicles, and other alternative-fuel vehicles (Delucchi and Lipman, 2001). This cost model is combined with a hybrid vehicle design and performance analysis using the ADVISOR vehicle simulation model. Five hybrid vehicle designs were examined for each vehicle type, for a total of 25 hybrid vehicle cases and a set of five baseline gasoline vehicles for comparison. It is found under various assumptions that combining the advanced package of vehicle improvements with mild vehicle hybridization provides the least-cost the hybrid vehicle option, with lifecycle costs very close to those of the baseline vehicles even using the relatively low historical gasoline price of $1.46 per gallon. However, with recent higher gasoline prices then many of the more fuel efficient, but costlier, hybrid vehicle designs become competitive from a lifecycle cost perspective.

Goedecke et al. (2007)
*price of energy – A1**
*non-energy operating costs – A1**
*external costs (physical units) – A1**
*external costs (dollars) – A1**
*other factors affecting lifetime cost – A1**

This paper uses a life cycle cost model (LLC) for alternative vehicle/fuel combinations and fuel saving options. They programmed the LCC model in HTML, JAVA and PERL. Most of the cost data are from Greene et al. (2004). GHG and air-pollution emission data are from three different sources: the Vehicle Certification Agency (VCA) on New Car Fuel Consumption and Exhaust emissions Figures; the ANL GREET model, and Beer et al. (2004). Externality damage costs are from Holland and Watkiss (2002).

The LLC model is available on the Internet at (http://vehiclesandfuels.memebot.com). The Methodology scheme of this paper is shown in Figure 1.

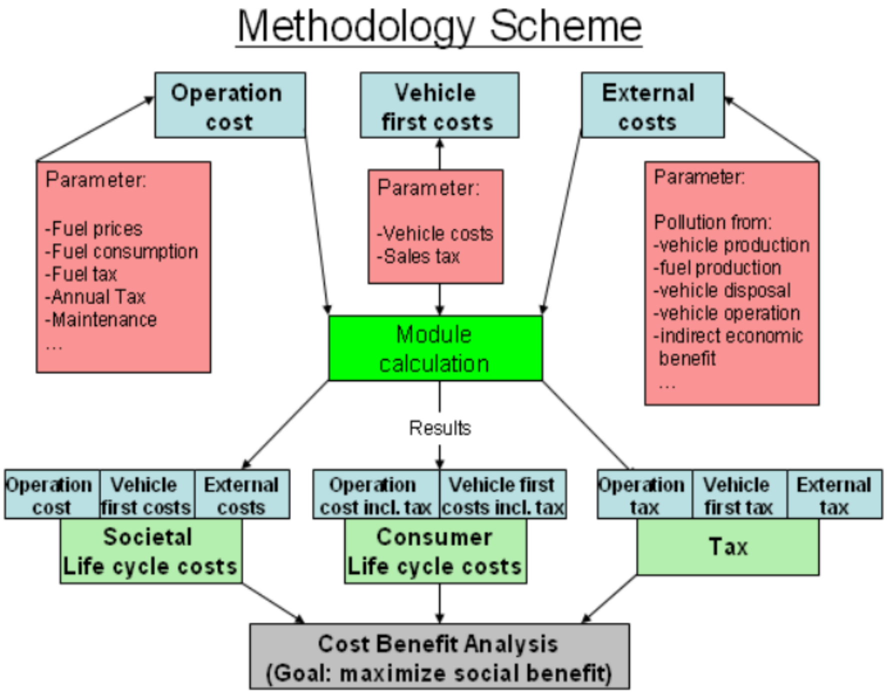


FIGURE 1. METHODOLOGY SCHEME OF THE COST BENEFIT ANALYSIS IN GOEDECKE ET AL. (2007) (THEIR FIGURE 2)

EPA (2009)
cost of major new components - A1
vehicle manufacturing cost – A1
vehicle retail cost – A1
non-energy operating costs – A1

This report gives an extremely detailed cost analysis for hybrid electric vehicles, plug-in hybrids, and full electric vehicles. The report considers several vehicle classes: subcompact, compact, midsize, large passenger car, large multi-purpose vehicle, small truck and large truck. Figure 2 shows the overall cost analysis flow chart. Figure 3 shows their method for estimating the net component and assembly cost for the Original Equipment Manufacturer (OEM).

In general, the costing methodology employed in this analysis is based on two primary processes: (1) the development of detailed production process flow charts (P-flows), and (2) the transferring and processing of key information, from the P-flows, into standardized cost worksheets (Figure 4).

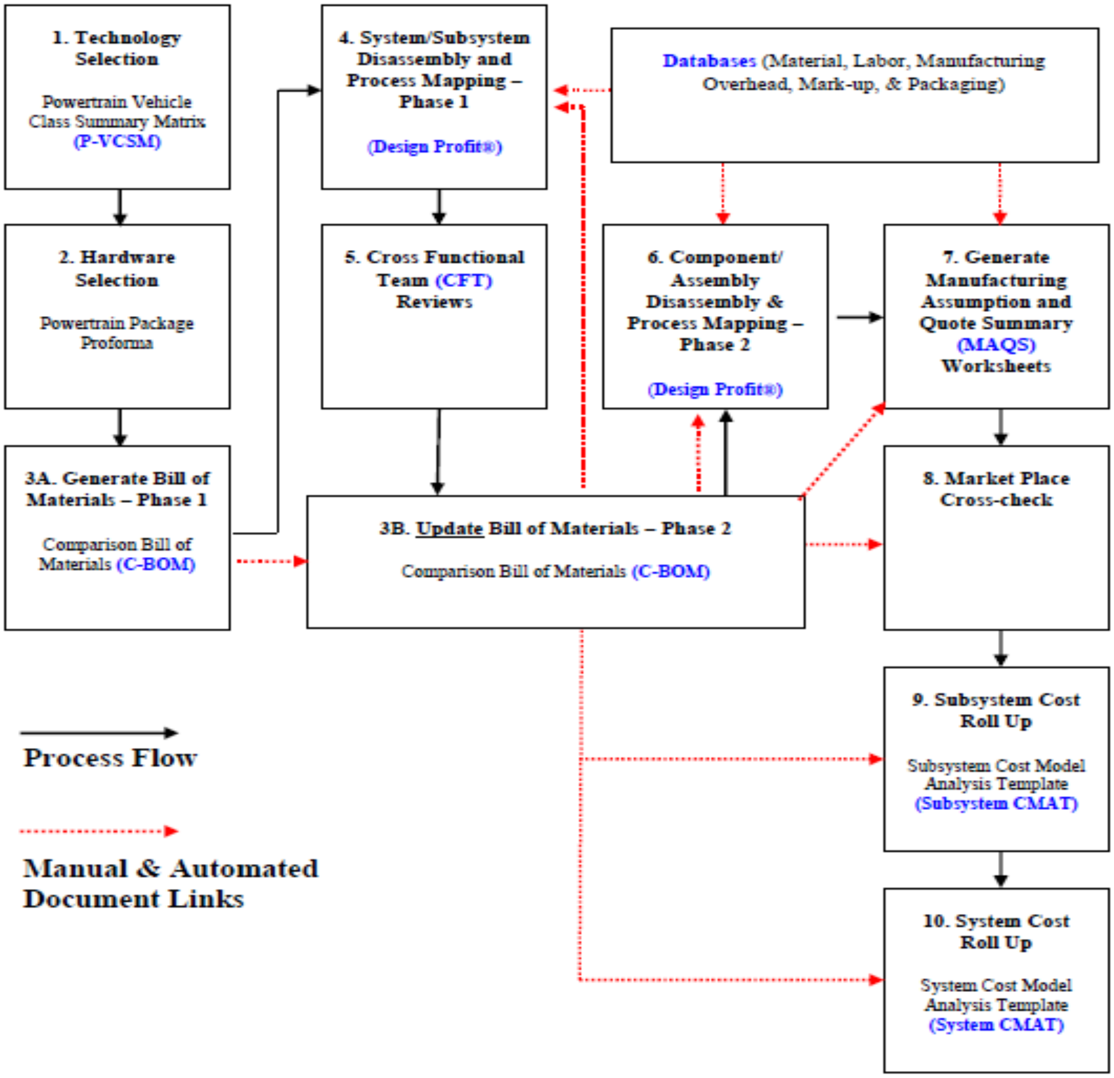


FIGURE 2. COST ANALYSIS PROCESS USED IN EPA (2009) (THEIR FIGURE 1-1)

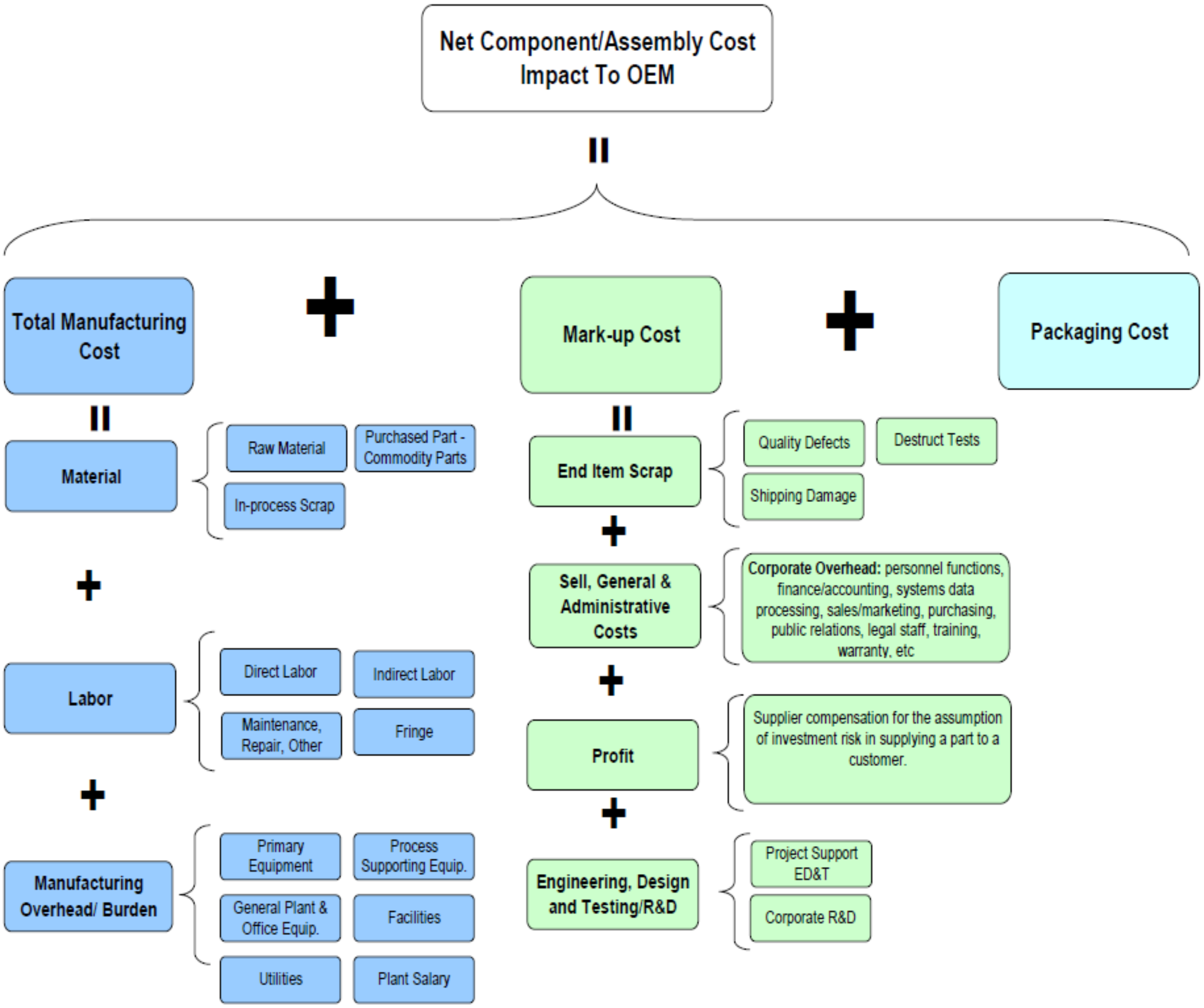
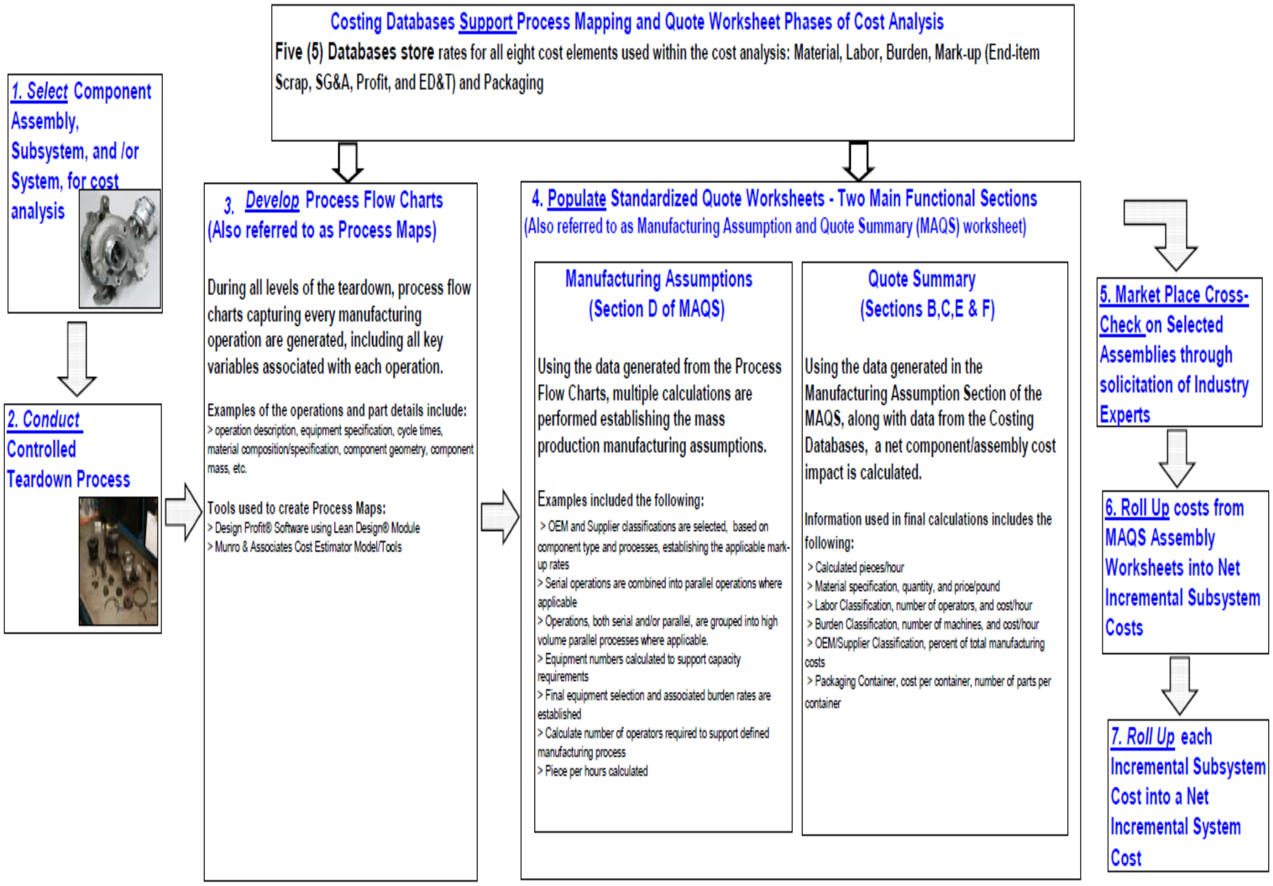


FIGURE 3. COMPONENT/ASSEMBLY COST METHOD USED IN EPA (2009) (THEIR FIGURE 5-1)



1. *Select* Component Assembly, Subsystem, and /or System, for cost analysis

2. *Conduct* Controlled Teardown Process

Costing Databases Support Process Mapping and Quote Worksheet Phases of Cost Analysis

Five (5) Databases store rates for all eight cost elements used within the cost analysis: Material, Labor, Burden, Mark-up (End-item Scrap, SG&A, Profit, and ED&T) and Packaging

3. *Develop* Process Flow Charts (Also referred to as Process Maps)

During all levels of the teardown, process flow charts capturing every manufacturing operation are generated, including all key variables associated with each operation.

Examples of the operations and part details include:
> operation description, equipment specification, cycle times, material composition/specification, component geometry, component mass, etc.

Tools used to create Process Maps:
> Design Profit® Software using Lean Design® Module
> Munro & Associates Cost Estimator Model/Tools

4. Populate Standardized Quote Worksheets - Two Main Functional Sections (Also referred to as Manufacturing Assumption and Quote Summary (MAQS) worksheet)

Manufacturing Assumptions (Section D of MAQS)

Using the data generated from the Process Flow Charts, multiple calculations are performed establishing the mass production manufacturing assumptions.

Examples included the following:
> OEM and Supplier classifications are selected, based on component type and processes, establishing the applicable mark-up rates
> Serial operations are combined into parallel operations where applicable
> Operations, both serial and/or parallel, are grouped into high volume parallel processes where applicable.
> Equipment numbers calculated to support capacity requirements
> Final equipment selection and associated burden rates are established
> Calculate number of operators required to support defined manufacturing process
> Piece per hours calculated

Quote Summary (Sections B,C,E & F)

Using the data generated in the Manufacturing Assumption Section of the MAQS, along with data from the Costing Databases, a net component/assembly cost impact is calculated.

Information used in final calculations includes the following:
> Calculated pieces/hour
> Material specification, quantity, and price/pound
> Labor Classification, number of operators, and cost/hour
> Burden Classification, number of machines, and cost/hour
> OEM/Supplier Classification, percent of total manufacturing costs
> Packaging Container, cost per container, number of parts per container

5. Market Place Cross-Check on Selected Assemblies through solicitation of Industry Experts

6. Roll Up costs from MAQS Assembly Worksheets into Net Incremental Subsystem Costs

7. *Roll Up* each Incremental Subsystem Cost into a Net Incremental System Cost

FIGURE 4. COSTING METHOD BASED ON PRODUCTION FLOW PROCESSES CHARTS IN EPA (2009) (THEIR FIGURE 4-1)

Sun et al. (2010)

cost of major new components – A1*
vehicle manufacturing cost – A1*
energy use – A1*
price of energy --- A1*
non-energy operating costs – A1*
external costs – A1*
other factors affecting lifetime cost – A1*

This paper estimates the societal lifetime cost of hydrogen FCVs and conventional gasoline internal combustion engine vehicles. As shown in their Research Framework (Figure 5), they use several models and sources in their analysis.

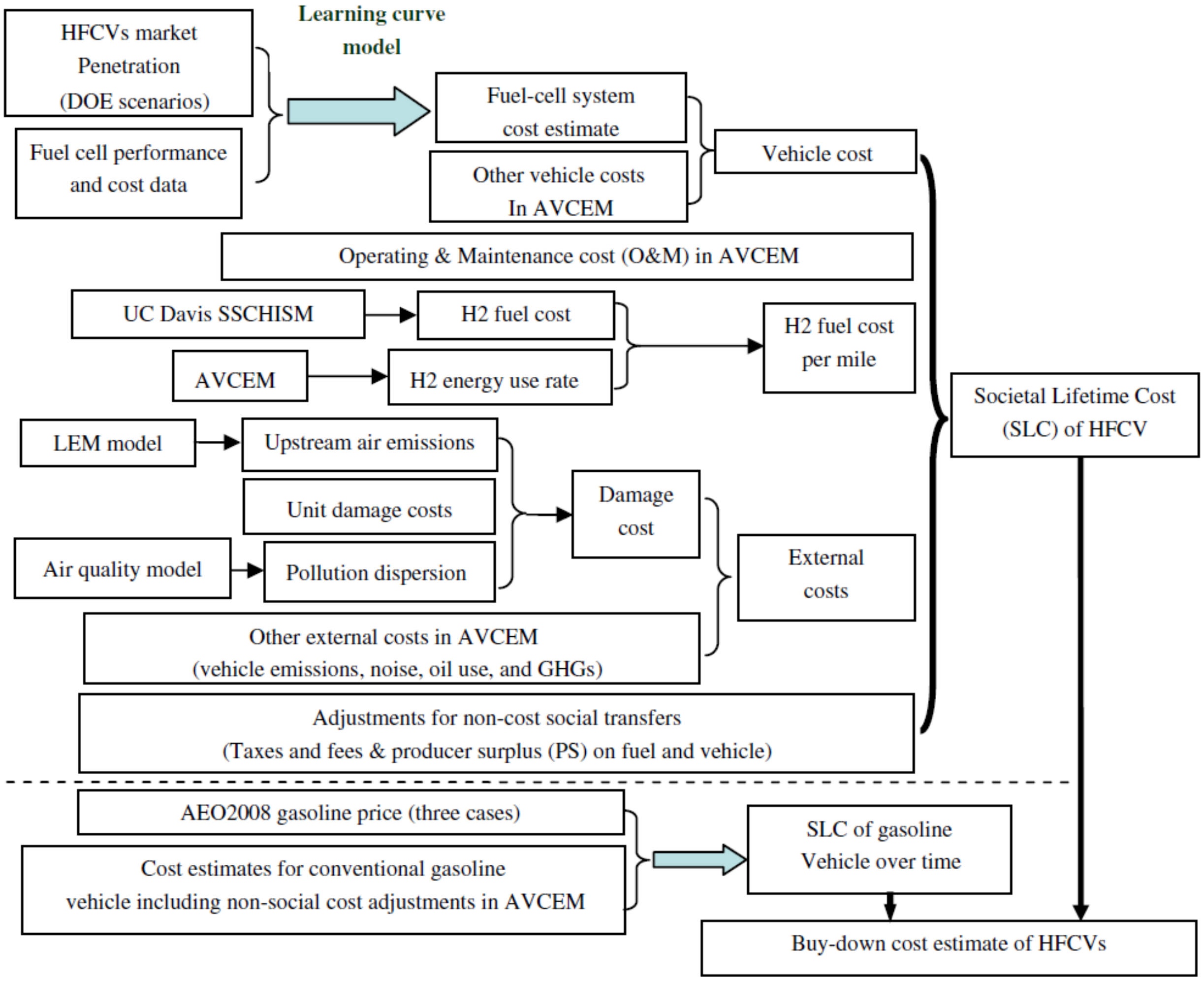


Figure 5. Energy and environmental impacts simulator in Sun et al. (2010) (Their Figure 1)

The main models they use are AVCEM (Advanced Vehicle Cost and Energy-use Model), UC Davis' SSCHISM (Steady State City Hydrogen Infrastructure System Model), and the LEM (Lifecycle Emissions Model). AVCEM is a vehicle performance and design model that allows users to design a vehicle to exactly satisfy performance and range specification with no more power and storage than is needed (Delucchi, 2005). SSCHISM estimates regional hydrogen infrastructure costs, emissions and primary energy requirements in an easy to use, flexible and interactive tool. The LEM estimates energy use, criteria pollutant emissions, and CO2-equivalent greenhouse-gas emissions from a variety of transportation and energy lifecycles (Delucchi et al., 2003).

Sun et al. estimate the external costs of oil use, air pollution, climate change and vehicle noise. The external costs of oil use per mile are calculated simply as the external cost per gallon of petroleum divided by the fuel economy. The fuel economy is calculated within AVCEM; Sun et al. use the results. The external cost per gallon is based upon a base-year value and an assumed rate of change. The estimates of g/mile motor-vehicle emissions are for model-year 2015 light-duty gasoline vehicles, taken from the LEM. Estimates of lifecycle CO2-equivalent GHG emissions also are from the LEM.

Camus and Farias (2012)
price of energy – A1
external costs (in physical units) – A1

This paper develops a series of functions to estimate energy costs and external costs including oil use and GHG emissions. They then use the EEEIS – Economic Energy and Environment Impacts Simulator (Camus et al., 2011) – developed in MATLAB, to solve a case study.

The EEEIS simulates "the effects of different EVs recharge profiles in the load diagrams for different seasons and typical days, accounting the energy and environment impacts for each scenario established as well as the hourly electricity spot prices expected for each scenario" (Camus et al., 2011). The main inputs and outputs can be seen in Figure 6 and sample results from the EEEIS can be seen in Figure 7.

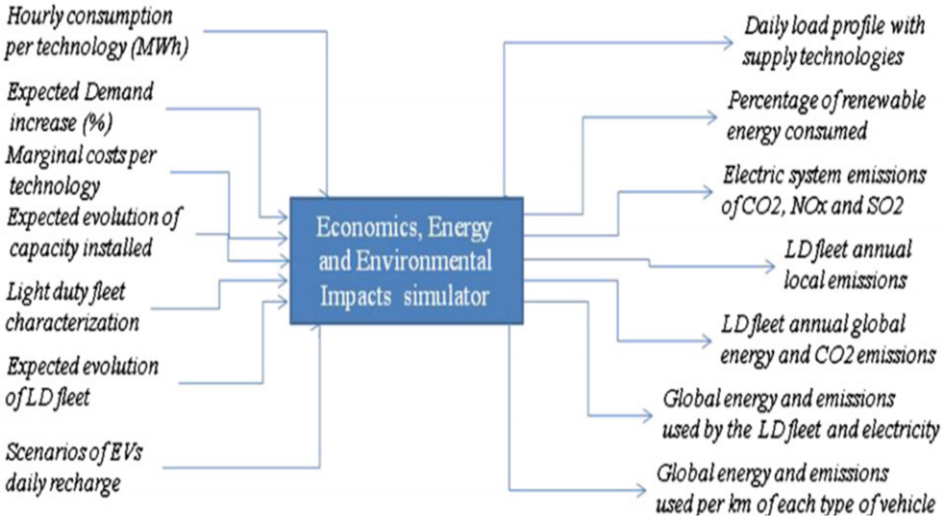
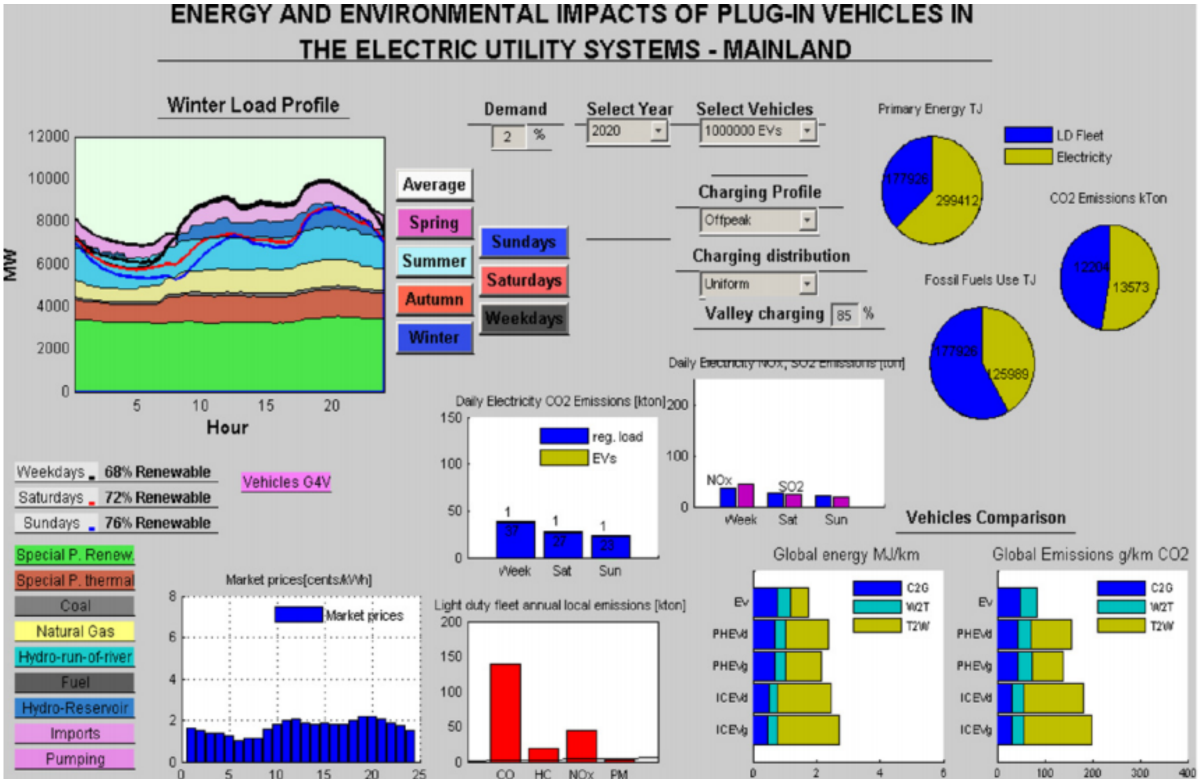


FIGURE 6. EEEIS INPUTS AND OUTPUTS (CAMUS AND FARIAS, 2012) (THEIR FIGURE 3)



ENERGY AND ENVIRONMENTAL IMPACTS OF PLUG-IN VEHICLES IN THE ELECTRIC UTILITY SYSTEMS - MAINLAND

Demand 2 %

Select Year 2020

Select Vehicles 1000000 EVs

Charging Profile Offpeak

Charging distribution Uniform

Valley charging 85 %

Weekdays 68% Renewable

Saturdays 72% Renewable

Sundays 76% Renewable

FIGURE 7. RESULTS FROM EEEIS (CAMUS AND FARIAS, 2012) (THEIR FIGURE 4)

NRC (2013)
cost of major new components – A1
energy use – A1
*price of energy – A1**
external costs (in physical units) – A1

The NRC assesses the potential of alternative fuels and alternative powertrains to reduce oil use and GHG emissions from the US LDV fleet by 80% by the year 2050. The report uses four models to estimate future vehicle characteristics, vehicle penetration into the market, and the impact on petroleum consumption and GHG emissions:

1) To estimate <u>energy use</u>, the NRC used an ICEV model developed by a consultant that projects vehicle efficiency out to 2050 by focusing on the reduction of energy losses from vehicle use. Their Appendix F documents their energy-use model.

2) To estimate the <u>costs of vehicle technologies</u>, the NRC developed a spreadsheet model of technology costs developed by the NRC. Their Appendix F documents their cost estimation methods and assumptions.

3) To estimate <u>GHG emissions and oil use,</u> the NRC modified and updated ANL's VISION model (Singh et al., 2003). The NRC then reviewed the literature and applied estimates of the social cost of carbon and the social cost of petroleum use.

4) To model <u>consumer demand</u> for vehicles, the NRC used the LAVE-Trans model.

Stephens et al. (2016)
*vehicle manufacturing cost – A1**
*energy use – A1**
*external costs (in physical units) – A1**

This report estimates the benefits of successfully developing advanced vehicle technologies, including battery-electric, hybrid, and fuel-cell vehicles. The incremental costs associated with advanced powertrains were estimated based on DOE cost and performance targets and cost models developed by Ricardo Engineering and the ANL Autonomie group (ANL, 2021a). The Autonomie model (ANL, 2021a) also was used to simulate vehicle energy use. GHG emissions and oil use were estimated using the GREET model (ANL, 2021b) and the VISION model (ANL, 2021c).

The researchers conclude that their analysis demonstrates that "successful VTO and FCTO programs will significantly reduce (1) oil consumption and oil dependence, (2) GHG emissions, and (3) consumer energy expenditures…[and that] these programs offer American drivers [other] benefits…including increased mobility, and reduced exposure to potential oil price shocks" (p. 55; inserts ours).

Lee and Thomas (2017)
*energy use – A1**
*external costs (in physical units) – A1**
*external costs (in dollars) – A1**

Lee and Thomas (2017) analyzed ownership costs for diesel, hybrid electric compressed natural gas, biofuel and electric class 6 freight trucks, including vehicle purchase, fuel, maintenance, diesel emission fluid, EVSE. Fuel economy was based on vehicle simulations, using the ADVISOR model, and costs were estimated from a variety of publicly available estimates. Upstream emissions were estimated using GREET, vehicle emissions were estimated using EPA's MOVES (EPA, 2014), and damage costs were estimated using the APEEP model (Muller, 2011).

DISCUSSION OF OTHER NOTEWORTHY STUDIES

Tsuchiya and Kobayashi (2004)

cost of major new components – A1

This paper proposes a series of functions to calculate the cost of a fuel-cell system. For each partial fraction of the function, the paper gave the detailed estimates. The basic data are from several references. The main function to estimate the cost is:

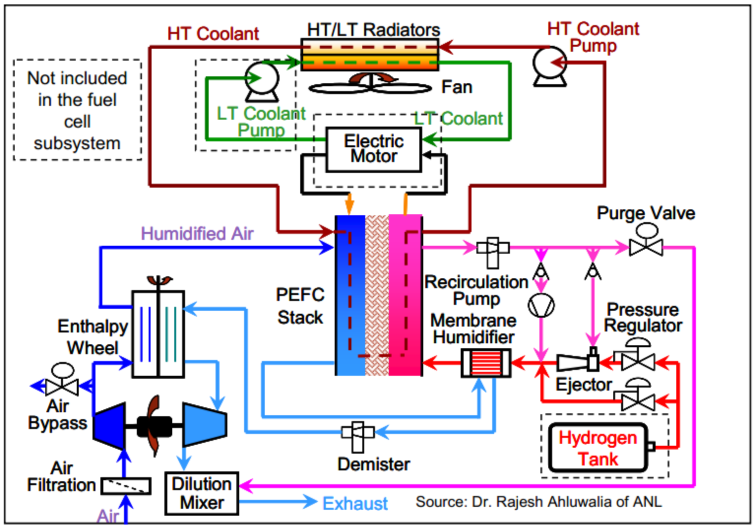
$$C = (C_m + C_e + C_b + C_{pt} + C_o)/P + C_a$$

Where, C is the fuel cell stack cost per kW ($/kW), C_m is the membrane cost ($/m^2), C_e is the Electrode cost ($/m^2), C_b is the bipolar plates cost ($ / m^2), C_{pt} is the cost of platinum catalyst loading($/m^2), C_o is the cost of peripheral materials ($/m^2), P is the power density per cell area (kW/m^2), and C_a is the assembly cost ($/kW).

Carlson et al. (2005)

cost of major new components – A1

This report gives a detailed cost estimate for an 80-kW direct hydrogen fuel cell system for the year 2005. The overall system configuration with major components is shown in Figure 8. The detailed estimates include the material cost, the manufacturing cost and the assembly cost. Figure 9 shows the cost breakdown for the balance of plant (BOP), and Figure 10 shows the cost breakdown for the fuel-cell stack.



Source: Dr. Rajesh Ahluwalia of ANL

FIGURE 8. OVERALL SYSTEM CONFIGURATION WITH MAJOR COMPONENTS IN CARLSON ET AL. (2005) (THEIR FIGURE 1)

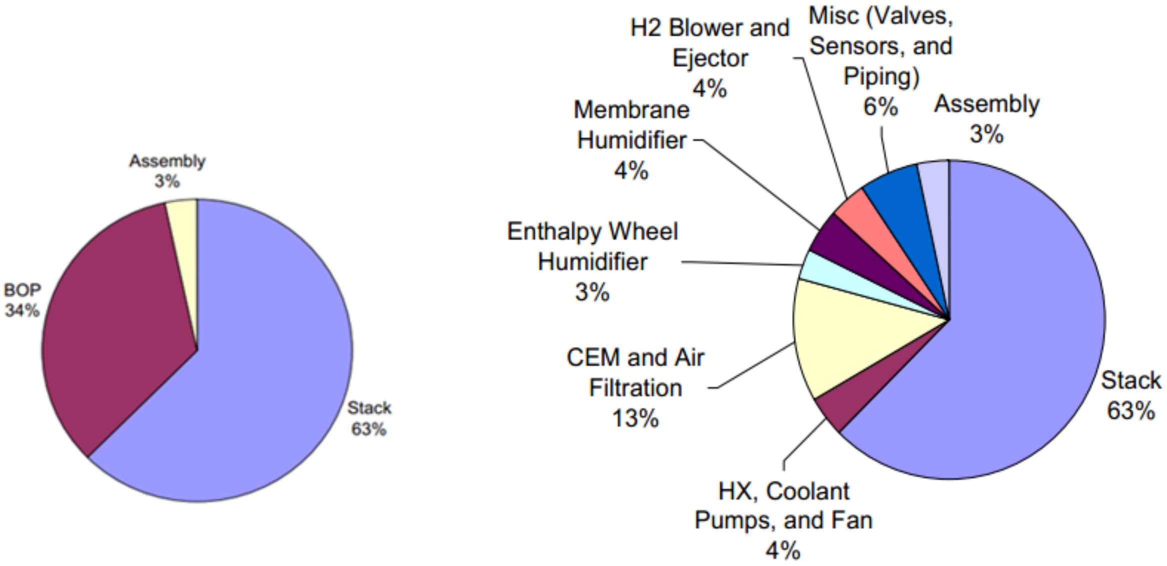


FIGURE 9. COST BREAKDOWN OF SYSTEM IN CARLSON ET AL. (2005) (THEIR FIGURES 2 & 3)

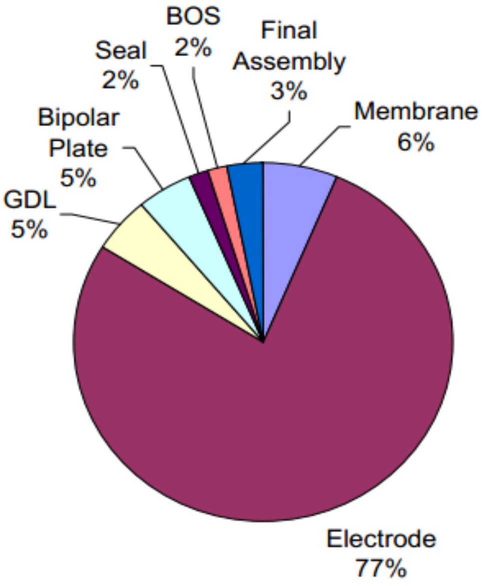


FIGURE 10: COST BREAKDOWN OF DIRECT HYDROGEN STACK IN CARLSON ET AL. (2005) (THEIR FIGURE 4)

Kalhammer et al. (2007)
*cost of major new components - A1**

The Kalhammer et al. Battery Technology Advisory Panel (BTAP) 2000 report gives detailed estimates of the cost of several kinds of batteries, including lithium-ion, nickel metal hydride, and the Zebra battery. This paper stated the estimate process and the results of the BTAP 2000 Panel report for each type of the batteries: The Panel focused its investigation on candidate EV battery technologies that promised major performance gains over lead acid batteries, appeared to have some prospects for meeting EV battery cost targets, and, at the time, were available from low volume production lines or, at least, laboratory pilot facilities" (BTAP, 2000).

Lasher et al. (2007)
cost of major new components - A1

This reference gives detailed estimates of every component of a fuel cell. They worked with ANL to define a 2007 fuel-cell system configuration and component specifications. They broke the fuel cell system into two main parts, which were then further disaggregated. Then, for each disaggregated component, they developed a cost model based on materials, design and manufacturing operations. They compare cost results for the years 2005 and 2007.

Lasher et al. use a bottom-up approach to determine manufacturing cost and the impact of economies-of-scale. They divided fuel cell system into two main parts: stack components and BOP (balance-of-plant) components. The stack components comprise the Catalyst Coated Membrane, Electrodes, Gas Diffusion Layer (GDL), Membrane Electrode Assembly (MEA), Bipolar Plates, and Seals/Gaskets;. The BOP components comprise the Radiator, Membrane Humidifier, Enthalpy Wheel, Humidifier, Compressor/Expander/Motor (CEM), H_2 Recirculation Pump, and H_2 Ejector. The cost of the component is estimated using the cost definition illustrated in Figure 11.

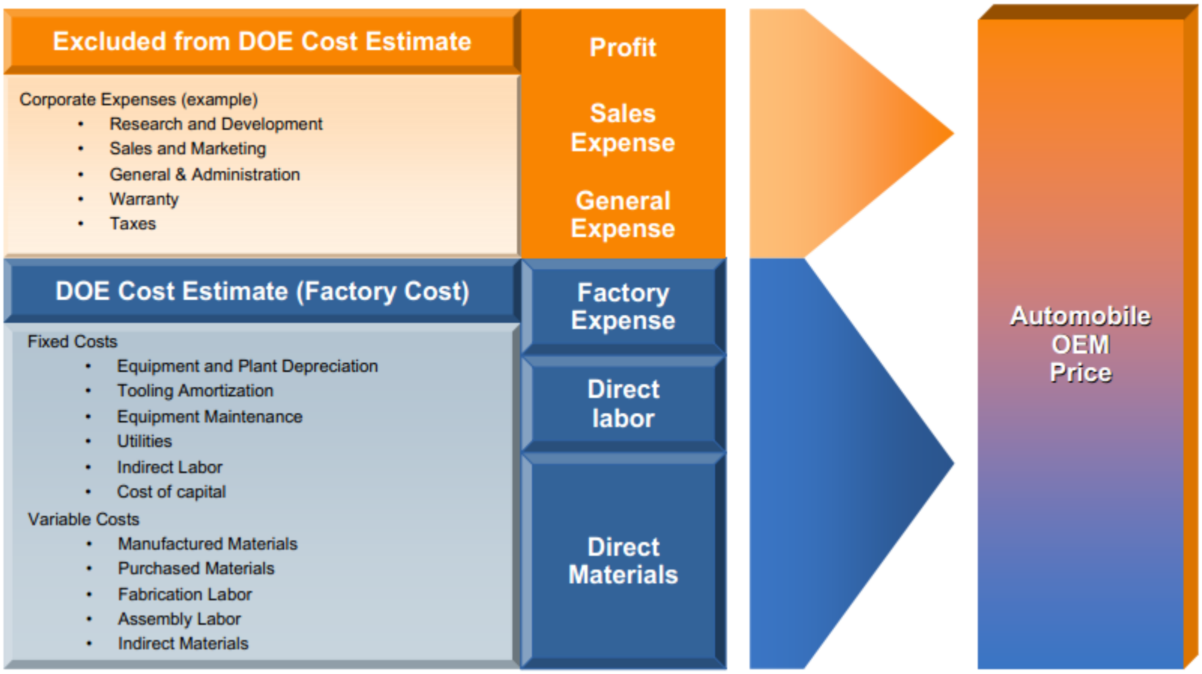


FIGURE 11. COST DEFINITION IN LASHER ET AL. (2007) (FROM THEIR PAGE 7)

James and Kalinoski (2007)
cost of major new components - A1

This paper proposes different technology schematics and a system analysis of the fuel cell system for the years 2007, 2010 and 2015. Based on the technology schematics, it gives detailed estimates of the cost of each part of the fuel cell system for each year, for production volumes of 1000, 30000, 80000, 130000, and 500000 units per year. The detailed estimates include the material cost, the manufacturing cost and the tooling cost.

Their cost formula is:

Estimated Cost = (Material Cost + Processing Cost + Assembly Cost) x Markup Factor

The manufacturing rate cost factors include material costs, the manufacturing method, machine rate, and tooling amortization, where the machine rate is equal to the sum of initial expenses and operating expenses divided by annual minutes of equipment operation. The methodology includes the cost of under-utilization of capital, the initial capital cost and installation, operating expenses include maintain or spare parts, and utilities and miscellaneous costs.

Ahluwalia and Wang (2007)

cost of major new components - A1

This paper presents a detailed cost analysis of near-term (2005) fuel cell systems, intermediate-term (2010) fuel cell systems, and far-term (2015) fuel-cell systems. The cost analysis for each fuel cell system includes the detailed cost of stack subsystem, air management subsystem, water management subsystem, thermal management subsystem and fuel management subsystem.

Kromer and Heywood (2009)
*energy use - A1**
*external costs - A1**

This paper assesses electric powertrains for PHEVs, FCVs, BEVs. To estimate "well-to-tank" energy, the paper employs EIA (2006) and GM/ANL (2005) projections. To estimate "tank-to-wheel" (or in-vehicle) energy use, the paper uses ADVISOR software simulations for year- 2030 vehicles operating over standard EPA drive cycles. This paper also uses projections from the Annual Energy Outlook 2006.

Thompson et al. (2009)
*external costs (in physical units) – A1**

To estimate changes in air quality, this paper uses a 3D Eulerian photochemical grid model, which predicts the spatial and temporal movement, production and depletion of air pollutants using data on emissions, meteorology, chemistry and deposition. The model used in this work is the Comprehensive Air Quality Model, with extensions (CAMx, www.camx.com). The modeling inputs for this were developed by the Central Regional Air Planning Association (CenRAP) for regional haze and visibility studies. A performance evaluation was conducted by ENVIRON and UC Riverside (2007).

Rogozhin et al. (2009)
*manufacturing cost – A1**
*retail cost – A1**

This paper estimated the ratio of total retail price (RP) to direct manufacturing cost (DMC) Direct manufacturing costs include "manufacturing labor and direct material costs, which can be estimated via reverse engineering or other approaches.". The retail cost is equal to the direct manufacturing cost plus indirect costs, which include "research and development, corporate operations, dealer support, and marketing and are difficult to estimate because many indirect costs are difficult to allocate to specific production activities or are not affected by levels of production." They estimated a weighted-average RP/DMC ratio of 1.46 for the automobile industry in 2007.

Delucchi and Lipman (2010)

Good literature review from 2010

Delucchi and Lipman review analyses of the lifetime cost of battery (BEV), Fuel-Cell (FCEV), and Plug-in Hybrid Electric Vehicles (PHEV). Figure 12 illustrates their conception of social lifetime cost. With this concept, and using data from a range of sources, the authors estimate costs for each major component of each type of EV.

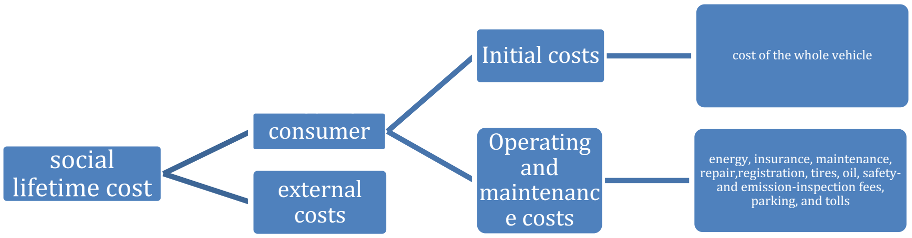


FIGURE 12. THE CONCEPT OF THE LIFETIME COST IN DELUCCHI AND LIPMAN (2010)

James et al. (2010)

cost of major new components - A1

This report gives detailed cost estimates of a fuel cell system for the years 2010 and 2015. The detailed estimates include the material cost, the manufacturing cost and the assembly cost. To assess the cost benefits of mass manufacturing, five annual production rates are examined for each technology level: 1000, 30000, 80000, 130000, and 500000 units per year. Table 7 shows their detailed system breakdown.

TABLE 7. SYSTEM SCHEMATICS IN JAMES ET AL. (2010)

FUEL CELL STACK	
Membrane	Membrane
catalyst ink & application	catalyst ink & application
Gas diffusion layer	Gas diffusion layer
Catalyst coated membrane, GDL and frame assembly	M&E hot pressing
	M&E cutting & slitting
	MEA frame/gaskets
Bipolar plates and coatings	Stamped bipolar plates
	Coolant gaskets(laser welding)
Assembly of stack	End gaskets
	End plate
	Current collector
	Stack compression
	Stack housing
	Stack assembly
Stack conditioning	Stack conditioning and testing

BALANCE OF PLANT	
Air compression system	CEM and motor controller
	Air mass flow sensor
	Air filter and housing
	Air ducting
Fuel circulation system	Inline filter for gas purity excursions
	Hydrogen high-flow ejector
	Hydrogen low-flow ejector
	Flow diverter valve
	Over-pressure cut-off valve
	Check valves
	Hydrogen purge valve
	Hydrogen piping
Humidification system	Membrane air humidifier
	Air precooler
	Demister
High & low-temperature cooling system	HTL coolant reservoir
	HTL coolant pump
	HTL coolant DI filter
	HTL thermostat and valve
	HTL radiator
	HTL radiator Fan
	HTL coolant piping
	LTL coolant reservoir (39%)
	LTL coolant pump (39%)
	LTL thermostat and valve (39%)
	LTL radiator (39%)
	LTL coolant piping (39%)
System controls	System controller
	Current sensors
	Voltage sensors
	Hydrogen sensors
System assembly	Wiring
	Belly pan for fuel cell system
	Mounting frames
	Fasteners for wiring and piping
	System assembly and testing

Dincer et al. (2010)
external costs (in physical units) – A2
external costs (in dollars) – A2

This paper gives a detailed analysis of the external costs of air pollution (AP) and greenhouse gas (GHG) emissions. They use a Toyota Corolla to represent a conventional vehicle, a Toyota Prius to represent a hybrid vehicle, a Toyota RAV4EV to represent an electric vehicle, a Honda FCX to represent a hydrogen fuel cell vehicle, and a Ford Focus H2-ICE to represent a hydrogen ICE vehicle. They propose several formulas to calculate the AP and GHG emissions for conventional vehicles and hybrid and electric vehicles. The reported results include the emissions per unit of vehicle curb mass and the emissions per 100 km of travel. They report GHG and air pollution emissions per MJ of several stages of the lifecycle of fuels and vehicles.

The formulas they use are as follows:

$AP = (m_{car}-m_{fc})*AP_m + m_{fc}*AP_{fc}$
$GHG = (m_{car}-m_{fc})*GHG_m + m_{fc}*GHG_{bat}$

Where, m_{car}, m_{bat}, and m_{fc} are, respectively, the masses of cars, NiMH batteries, and the fuel cell stack; AP_m, AP_{bat}, and AP_{fc} are AP emissions per kilogram of conventional vehicle, NiMH batteries, and the fuel cell stack; and GHG_m , GHG_{bat}, and GHG_{fc} are GHG emissions per kilogram of conventional vehicle, NiMH batteries, and fuel cell stack.

Elgowainy et al. (2010)
energy use – A1
external costs (in physical units) – A1

This paper uses the GREET model to estimate the lifecycle energy use and GHG emissions associated with various transportation pathways.

Sioshansi et al. (2010)
*external costs (in physical units) – A1**

The models in this paper are formulated using AMPL 12.1 and solved using cplex 12.1. The analysis considers two emission sources, generators and vehicle tailpipes, and three types of emissions, CO2, SO2, and NOx. Generator emissions are further broken down into the emissions of generators in Ohio and emissions in the rest of the PJM (Pennsylvania, New Jersey, Maryland Interconnection) market. The emissions of Ohio generators are estimated using emission factors per unit of fuel input. These, in turn, are estimated by combining data on output-based emission rates, from the Continuous Emissions Monitoring System (CEMS) (reported by the U.S. Environmental Protection Agency (EPA), with data on fuel burned. Emissions from generators in the rest of the PJM market are estimated by using historical hourly marginal fuel mix data http://www.monitoringanalytics.com/data/marginal_fuel.shtml.

EPA (2010)
external costs (in physical units) – A1
external costs (in dollars) – A1

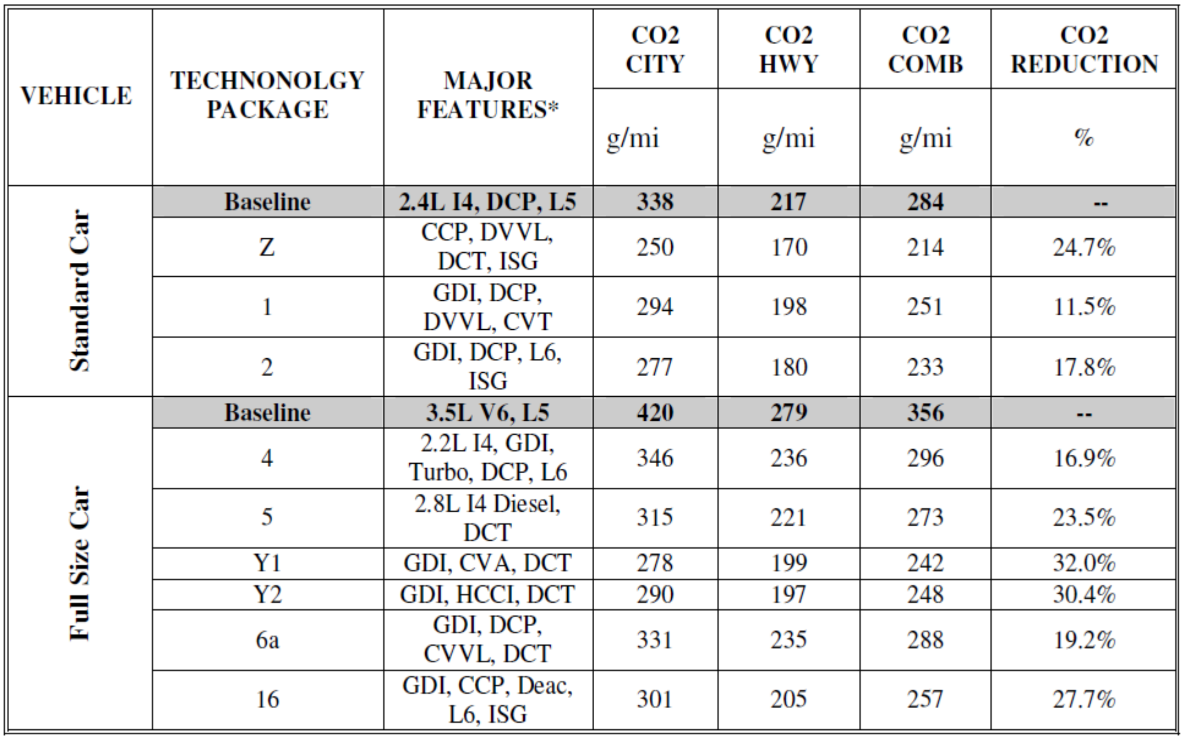
EPA used two models to derive downstream (tailpipe) emission impacts. Computation algorithms and achieved CO2 levels were derived from EPA's Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA). Non-CO2 emissions were calculated using data from EPA's Motor Vehicle Emission Simulator (MOVES2010). OMEGA is used to predict the most likely paths by which manufacturers would meet tailpipe CO2 emission standards. OMEGA "applies technologies with varying degrees of cost and effectiveness to a defined vehicle fleet in order to meet a specified GHG emission target and calculates the costs and benefits of doing so."

EPA used the ADVISOR model (discussed above) to get estimates of CO2 emissions for the combined city and highway test cycles on the EPA Federal Test Procedure (FTP). Table 8 shows the technology package results compared with the baseline vehicle.

EPA et al. (2010)
cost of major new components - A1

This report estimates the costs of HEVs, PHEVs, EVs, and FCEVs. They use a battery cost model developed by ANL for the Vehicle Technologies Program of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy. The ANL battery cost model provides unique battery pack cost estimates for each of the three major types of electrified vehicles. The results are as below in Table 9 (their table 3.2-1 and table 3.2-2):

TABLE 8. CO2 EMISSION ESTIMATES IN EPA (2010) (THEIR TABLE 1-22)



VEHICLE	TECHNONOLGY PACKAGE	MAJOR FEATURES*	CO2 CITY	CO2 HWY	CO2 COMB	CO2 REDUCTION
			g/mi	g/mi	g/mi	%
Standard Car	**Baseline**	**2.4L I4, DCP, L5**	**338**	**217**	**284**	**--**
	Z	CCP, DVVL, DCT, ISG	250	170	214	24.7%
	1	GDI, DCP, DVVL, CVT	294	198	251	11.5%
	2	GDI, DCP, L6, ISG	277	180	233	17.8%
Full Size Car	**Baseline**	**3.5L V6, L5**	**420**	**279**	**356**	**--**
	4	2.2L I4, GDI, Turbo, DCP, L6	346	236	296	16.9%
	5	2.8L I4 Diesel, DCT	315	221	273	23.5%
	Y1	GDI, CVA, DCT	278	199	242	32.0%
	Y2	GDI, HCCI, DCT	290	197	248	30.4%
	6a	GDI, DCP, CVVL, DCT	331	235	288	19.2%
	16	GDI, CCP, Deac, L6, ISG	301	205	257	27.7%

TABLE 9. BATTERY PACK COST ESTIMATES FROM BATPAC MODEL USED BY EPA ET AL. (2010) (THEIR TABLES 3.2-1 AND 3.2-2)

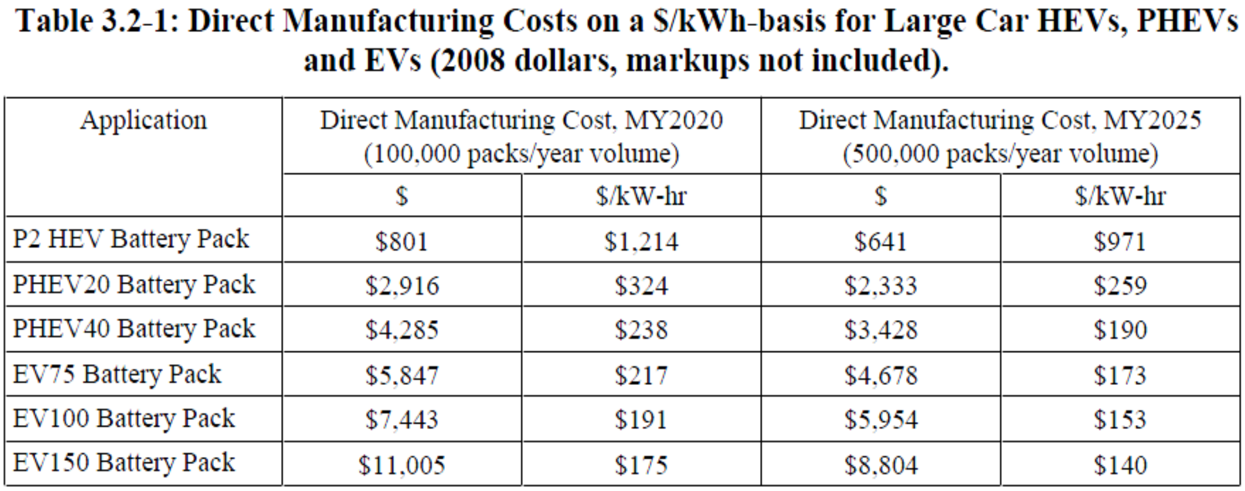
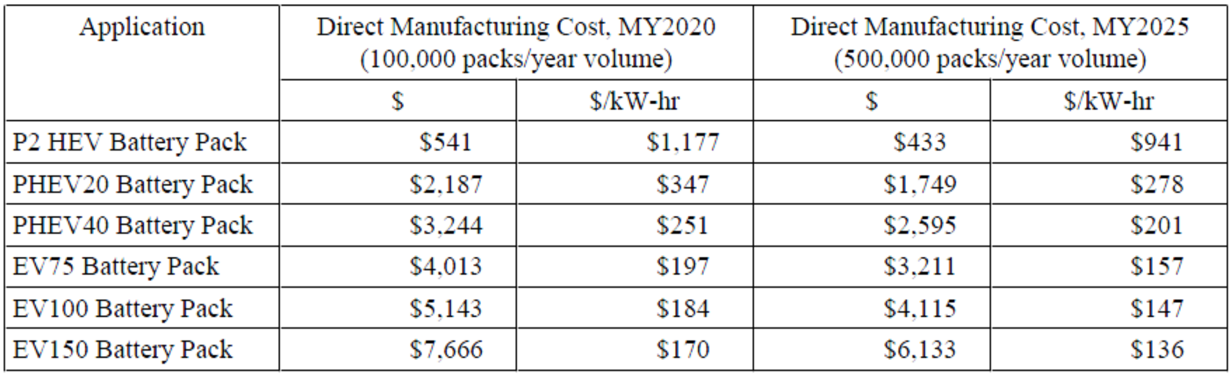


Table 3.2-1: Direct Manufacturing Costs on a $/kWh-basis for Large Car HEVs, PHEVs and EVs (2008 dollars, markups not included).

Application	Direct Manufacturing Cost, MY2020 (100,000 packs/year volume)		Direct Manufacturing Cost, MY2025 (500,000 packs/year volume)	
	$	$/kW-hr	$	$/kW-hr
P2 HEV Battery Pack	$801	$1,214	$641	$971
PHEV20 Battery Pack	$2,916	$324	$2,333	$259
PHEV40 Battery Pack	$4,285	$238	$3,428	$190
EV75 Battery Pack	$5,847	$217	$4,678	$173
EV100 Battery Pack	$7,443	$191	$5,954	$153
EV150 Battery Pack	$11,005	$175	$8,804	$140

Table 3.2-2: Direct Manufacturing Costs on a $/kWh-basis for subcompact HEVs, PHEVs and EVs (2008 dollars, markups not included).



Application	Direct Manufacturing Cost, MY2020 (100,000 packs/year volume)		Direct Manufacturing Cost, MY2025 (500,000 packs/year volume)	
	$	$/kW-hr	$	$/kW-hr
P2 HEV Battery Pack	$541	$1,177	$433	$941
PHEV20 Battery Pack	$2,187	$347	$1,749	$278
PHEV40 Battery Pack	$3,244	$251	$2,595	$201
EV75 Battery Pack	$4,013	$197	$3,211	$157
EV100 Battery Pack	$5,143	$184	$4,115	$147
EV150 Battery Pack	$7,666	$170	$6,133	$136

EPA (2011)
cost of major new components - A1

The objective of this report is to determine incremental direct manufacturing costs for a set of advanced light-duty vehicle technologies. EPA uses the P-flow and standardized worksheet methods described for EPA (2009). The analysis is based on a detailed teardown and costing of the hardware differences due to the use of power-split HEV technology in the 2010 Ford Fusion HEV versus the equivalent 2010 Ford Fusion conventional powertrain vehicle. The report uses the System Cost Model Analysis Template (CMAT) to display and roll-up all the cost associated with a particular subsystem, system or vehicle.

EPA and NHTSA (2011)
energy use – A1
external costs (in physical units) – A1

Section 4 of this report focuses on the use of vehicle simulation modeling for assessing tailpipe GHG emissions and fuel consumption for medium-duty and heavy-duty vehicles. They provide a detailed explanation of the EPA and NHTSA Vehicle Compliance Model, including the purpose and scope, the model code description, and how to use the model in MATLAB-based Graphical User Interface (GUI).

James et al. (2011)
cost of major new components - A1

This update of James et al. (2010) gives a detailed cost estimate for a fuel-cell system for the target year 2011. The estimation method is the same as in James et al. (2010).

Pasaoglu et al. (2011)
*external costs (physical units) – A1**

This study uses a spreadsheet model, programmed in Visual Basic, to analyze power-train deployment scenarios for passenger cars and light commercial vehicles in the EU through 2050.. It quantifies and assesses the potential impact of these scenarios on well-to-wheel (WtW) CO_2 emission reductions, primary energy demand, and cost to vehicle owners.

The model comprises a vehicle stock module, a demand module, a stock-turnover module, a WtW and fuel-consumption module, and an output module. The WtW and fuel consumption module considers annual vehicle mileage, vehicle ages, the evolution of biofuel-share in the fuel mix, technological improvement rates, the current and future electricity generation mix, and the WtT CO_2 emissions of the fuels/energy production pathways. Technology costs are estimated as a function of initial costs in the base year, the evolution of demand, and technological learning as production volumes increase.

EPA and NHTSA (2012)
*cost of major new components – A1**
*manufacturing cost - A1**

In this Joint Technical Support Document for the Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, EPA and NHTSA (2012) examine costs for HEVs, PHEVs, EVs, and FCEVs. The agencies use a battery cost model developed by ANL for the Vehicle Technologies Program of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy. The ANL battery-cost model allows users to estimate unique battery pack costs using user-customized input sets for different types of electrified powertrains, including strong hybrids, PHEVs, and BEVs.

The battery cost for each type of EV is reported in their section 3.4.3.

The report presents a cost analysis based on tear-down studies conducted during a prior (2012-2016) rulemaking. The tear-down studies "involve breaking down a technology into its fundamental parts and manufacturing processes by completely disassembling vehicles and vehicle subsystems and precisely determining what is required for its production" (EPA and NHTSA, 2012, p. 3-8).

Rousseau et al. (2015)
energy use – A1

Rousseau at al. (2015) estimated costs of vehicles of multiple powertrain types based on vehicle simulations, and analyzed how ownership costs of such vehicles depend on conditions (fuel prices, taxes, driving distances) representative of Europe and of the United States. rates. They show that analyzing costs under different conditions (vehicle and fuel prices, costs of depreciation, maintenance, and repair, driving distances, incentives, etc.) leads to different conclusions about magnitudes of important costs, and in some cases, which powertrains have lower ownership costs.

CARB (2015f)

CARB (2015f) assessed medium- and heavy-duty battery electric vehicles and compared technology readiness and costs with those of other drivetrain types in in applications including shuttle bus, transit bus, school bus, delivery van, drayage truck, and freight truck. Costs estimates of batteries and other components and incremental prices of BEV vs. vehicles with other drivetrain types were based on earlier studies, including Meszler et al. (2015), CALSTART (2013), and Gallo and Tomic (2013). CARB (2015f) reported payback time for electric medium duty trucks could be as short as 3 to 5 years with incentives offsetting some of the higher purchase price, and likewise that electric transit buses could have payback times of a few years with incentives. They noted the lack of sufficient data to estimate payback times of other heavy-duty BEVs. They also noted that prices of medium- and heavy-duty BEVs were expected to decrease significantly in the future.

Palmer et al. (2018)
*vehicle retail cost – A1**
*other factors affecting lifetime cost – A1**

Palmer et al. (2018) compared costs of specific HEV, PHEV, BEV, and ICEV models under conditions relevant to different countries or states. They reviewed earlier ownership costs studies (all of which are included in our review) and found many did not include some important cost element, such as maintenance, salvage or resale value, taxes, or insurance, and studies assumed different discount

ICF (2019)
*price of energy – A1**

ICF (2019) estimated ownership costs of current (as of 2019) and MY 2030 diesel, electric, and natural gas medium-duty and heavy-duty trucks, and fuel-cell heavy-duty trucks. Considering costs of vehicle purchase, fuel, maintenance, and infrastructure (for electric and fuel cell trucks), they reported that currently electric class 8 trucks had higher ownership costs than diesel trucks, even with incentives, but that by 2030, electric class 8 trucks (including drayage and refuse trucks) and transit buses could be the cheapest to own even without incentives. For class 6 regional haul freight trucks natural gas had the lowest TCO, and for school buses diesel had the lowest TCO, in 2030.

CARB (2019)

The California Air Resources Board (CARB, 2019) analyzed ownership costs of a class 3 passenger van, a class 6 stepvan, and a class 8-day cab tractor used in regional service. They estimated that the total cost of ownership (TCO) of a class 6 battery electric stepvan over 12 years could be less than that of a comparable diesel stepvan, depending on assumptions about electricity costs and the drive cycle. The TCO of the class 8-day cab tractor could be become lower than that of its diesel counterpart by 2024, if battery costs decrease sufficiently. Fuel cell trucks may reach TCO parity with diesel trucks by 2030 or sooner if they have access to fueling stations that are highly utilized. For the TCO of battery electric trucks ARB included the cost of electric charging equipment purchase and installation costs as well as revenue generated from low carbon fuel standard credits for electricity. They noted that the relative TCO of diesel and electric vehicles depended on the assumed driving distance and costs of electric charging infrastructure, which could vary widely.

Murray and Glidewell (2019)

A number of recent papers on ownership costs of heavy-duty vehicle cite the annual report issued by the American Transportation Research Institute on the operational cost of trucks (Murray and Glidewell 2019). The ATRI reports include average annual labor and vehicle costs, as shown in Figure 13. The 2019 report (Murray and Glidewell, 2019) provides valuable data on current costs of long-haul diesel trucks. Labor and fuel costs are the two largest costs for commercial freight carriers, with labor costs increasing sharply since 2012. Although fuel costs often have been volatile, they have been relatively low the past few years due to a drop in diesel prices and improvements in truck fuel economy. Truck payments are the third highest cost-category and have been rising since 2013.

Murray and Glidewell (2019) estimate that maintenance and repair costs have declined from $0.17 per mile in 2008 to $0.10 per mile in 2018, while tire costs have been fairly consistent at $0.04 per mile in 2018 (Figure 2.1-1). Given an average freight truck VMT of 88,250 in 2018, maintenance and repair and tire costs were $12,400. Finally, they note that the EPA 2007 PM2.5 emission standards required the installation of a diesel particulate filter (DPF), which must occasionally be "regenerated" to remove accumulated material from the filter. This increased maintenance and repair costs for fleets with urban duty-cycles but not for trucks with highway-duty cycles, because highway driving enables "passive" regeneration of the DPR.

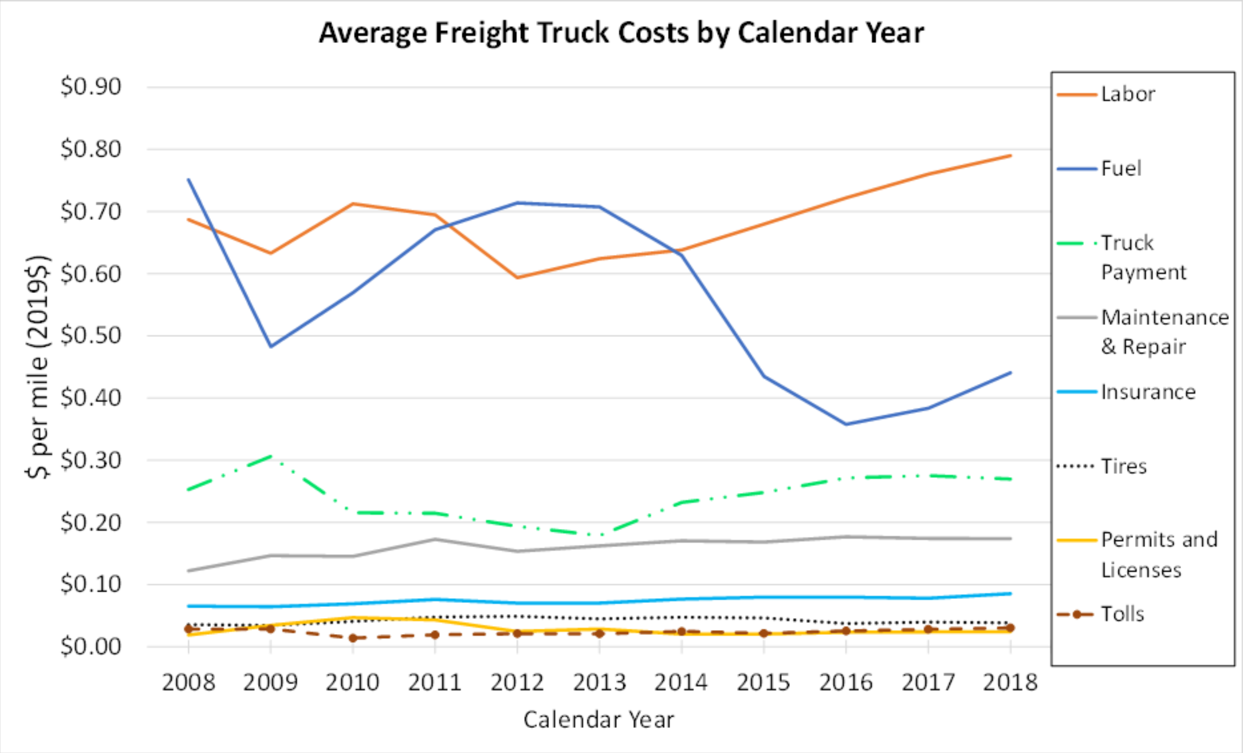


FIGURE 13. AVERAGE FREIGHT TRUCK COSTS BY CALENDAR YEAR (HOOPER AND MURRAY 2017; MURRAY AND GLIDEWELL, 2019)

Sripad and Viswanathan (2019)

Sripad and Viswanathan (2019) examined ownership costs of class 8 long-haul electric trucks in comparison with diesel trucks. They modeled fuel economy of comparable diesel and electric trucks under a range of driving conditions and estimated distributions of ownership costs for ranges of inputs: diesel fuel and electricity prices, annual driving distance, differences in vehicle price and maintenance cost (the battery truck was assumed to have a higher price but lower maintenance costs), and other operating costs. They found that battery trucks with an effective range of 400 miles could be less expensive to own that diesel trucks. They found that the payback time of an electric truck vs. a diesel truck was sensitive to assumptions about battery lifetime and replacement cost, the initial vehicle price difference, prices of diesel fuel and electricity and the annual distance driven, but less sensitive to the difference in costs of maintenance and repairs or fuel economy.

Satterfield and Nigro (2020)

Satterfield and Nigro (2020) analyzed ownership costs of electric and diesel medium- and heavy-duty trucks in different use cases, including heavy-duty long-haul, heavy-duty short-haul, terminal tractor, delivery vans (two sizes), straight trucks (medium- and heavy duty), and cargo vans. They found that in most cases analyzed electric trucks would have a higher cost of ownership under current conditions, but that results depended strongly on details of the use case considered. They estimated that the costs of charging electric trucks could be very high if trucks were charged for long times during normal work hours and thus entailed a high lost productivity ("downtime") cost. However, if electric trucks can charge at a depot during non-service hours, e.g., overnight, the downtime cost could be eliminated and lower-power and less expensive charging equipment could be used. Other factors were significant but less influential than charging costs, including the higher price of electric vehicles, vehicle utilization (higher utilization favoring electric vehicles), and potentially lower maintenance cost for electric vehicles. Finally, they analyzed the TCO under thousands of combinations of input variables, and found a very wide range of results: the ratio of the TCO of electric to diesel vehicles ranged from about one-half to over 5, indicating the strong dependence on inputs across the many the use cases analyzed.

Harto (2020)
non-energy operating costs - A2
other factors affecting lifetime costs - A2

This study by Consumer Reports "relies on new data on electric vehicle depreciation rates and maintenance and repair costs, along with real world average vehicle prices, to estimate how much today's most popular EVs can save consumers when compared with similar ICE vehicles" (Harto, 2020, p. 3). Depreciation rates are based on projections from ALG, a data and analytics subsidiary of automotive pricing and information website TrueCar. ALG bases its projections on "proprietary algorithms and data from millions of real-world new and used vehicle transactions" (Harto, 2020, p. 5). These data indicate that EVs will retain their value about as well as will comparable ICEs.

Estimates of maintenance and repair costs are based on results from Consumer Reports' 2019 and 2020 spring reliability surveys, which among other things ask individual drivers to "estimate how much they spent on repairing and maintaining their vehicle over the past 12 months, as well as how many miles they drove in the past 12 months, and how many total miles their vehicle has on it" (Harto, 2020, p. 9). Analysis of these survey data indicate that EV owners are paying half as much as are ICE owners for maintenance and repair.

NAS (2020)
Comprehensive literature review of some elements of the TCO of MDTs and HDTs

This report by the National Academy of Sciences (NAS) is a comprehensive, 400-page techno-economic evaluation of technologies to reduce the fuel use and GHG emissions of MDTs and HDTs. The NAS considered powertrain modifications, alternative fuels, and battery-electric vehicles. They provided a comprehensive review of estimates of: 1) the technical characteristics and manufacturing cost of batteries; 2) the climate, air-quality, and energy-security benefits of different fuel and technology options; and 3) the indirect-cost component of the total retail price (e.g., ,corporate costs, sales costs, engineering costs, and engineering and advertising).

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