# Quantifying the Impacts of Micro- and Mild- Hybrid Vehicle Technologies on Fleetwide Fuel Economy and Electrification

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**ABSTRACT**

Micro- and mild- hybridization (jointly labeled as M-HEV) is gaining popularity as a cost-effective technology for fuel economy improvement, but whether and how M-HEV may compete against less efficient conventional internal combustion engine vehicles (ICEV), more efficient full hybrid electric vehicles (HEV), and plug-in electric vehicles (PEV) is not well understood. This study aims at evaluating the impact of the market adoption of M-HEV on the average fuel economy of the new vehicle fleet and on the sales share of PEVs. The study reviews recent sales trends and market forecasts, and uses published estimates of manufacturing cost and fuel economy of M-HEV with an existing discrete choice model (Market Acceptance of Advanced Automotive Technologies or MA3T) to project the market penetration and impacts of M-HEV under different scenarios of M-HEV choice positions, designed to enhance conclusion robustness. It is found that among engine-based powertrain choices, micro-HEV appears to be the most cost-effective, followed by ICEVs, mild-HEV and finally full HEVs. M-HEV technologies are likely to improve fleetwide average fuel economy without significant adverse effects on sales of plug-in electric vehicles, and are likely to remain highly competitive outside PEVs through 2050.

## 1. Introduction

As fuel economy standards become more stringent worldwide, automobile manufacturers are considering and implementing different degrees of vehicle hybridization and electrification. Full hybrid electric vehicles (HEV) offers much better fuel economy but also costs significantly more, compared to conventional internal combustion engine vehicles (ICEV) and thus has only slowly penetrated the market. Micro- and mild- hybridization (jointly labeled as M-HEV) has recently gained popularity as a cost-effective technology for fuel economy improvement, but whether and how M-HEV may compete against less efficient ICEVs, more efficient HEVs, and PEVs is a policy-relevant question and yet to be quantitatively understood.

The objective of this study is to investigate the market impacts of M-HEV adoption on average fuel economy of the new vehicle fleet and sales shares of PEVs in the U.S. vehicle market, for the potential interests of fuel economy policy makers and industry decision makers. Increased degrees of hybridization lead to improved fuel economy, though at increased manufacturing costs. It is expected that M-HEV will help original equipment manufacturers (OEMs) comply with the Corporate Average Fuel Economy (CAFE) standards and improve average fuel economy. This theoretically implies reduced needs for high sales of plug-in electric vehicles (PEVs) for CAFE compliance. This study will explore the extent to which market development of M-HEV will affect fleet average fuel economy and affect the market penetration of PEVs. The study scope includes reviewing the current market trends for hybridization technology, summarizing the costs and potential improvement of fuel economy through M-HEV technologies, conducting scenario analyses using the Market Acceptance of Advanced Automotive Technologies (MA3T) model to estimate market share of different powertrains and to quantify the impacts of M-HEV market penetration on fleetwide average fuel economy.

The consumer uptake of advanced fuel economy technologies depends on their cost and effectiveness. HEV sales have been shown correlated with gasoline prices, with consumers more willing to pay for fuel savings when gasoline prices are high (Diamond, 2009). HEV sales can also be encouraged by policy drivers, such as tax credits for fuel-efficient vehicles or preferential access to high-occupancy vehicle lanes (Beresteanu and Li, 2011). M-HEV technologies provide an opportunity for fuel economy improvement over conventional internal combustion engine vehicles (ICEVs) with limited extra production costs (National Research Council, 2015; Xie et al., 2017). Using the previous work studying the advantages of M-HEV at the component and vehicle level, this study aims to quantify the fleetwide impact of M-HEV from the market perspective. This study uses values for fuel economy and vehicle manufacturing cost from projections by the National Research Council (National Research Council, 2015) and the Autonomie model (Islam et al., 2018), as inputs via the MA3T model, to estimate sales of M-HEV technologies in the context of an increasingly electrified vehicle market.

Table 1 shows the vehicles that are included in the MA3T in this study. Conventional ICEVs are defined by those which do not have the capability to automatically stop and start the engine when the vehicle is not moving. Micro-HEVs are ICEVs which do have stop-start capability. Mild-HEVs are defined as the vehicles that have an integrated starter-generator and a more powerful 48-Volt battery which can assist in vehicle propulsion. Full hybrids have regenerative braking and a larger battery which can be used for short-range unassisted propulsion. Plug-in hybrid electric vehicles (PHEV) can be powered by electricity and gasoline and drive moderate distances (15-50 miles) on electricity, while battery electric vehicles (BEVs) are powered exclusively by electricity (Ou et al., 2019).

**Table 1.** Degrees of vehicle hybridization and electrification

| Vehicle | Voltage | Regenerative braking / Stop-start | Battery use |
|---------|---------|-----------------------------------|-------------|
| Pure ICEV | 12V | | Battery for starter |
| Micro-HEV | 12V | Stop-start | Battery for accessories |
| Mild-HEV | 48V | Regenerative braking | Battery able to assist propulsion |
| Full HEV | ~200V | Regenerative braking | Battery for short-range unassisted propulsion |
| PHEV | ~200V | Regenerative braking | Battery for long-range unassisted propulsion |
| BEV | ~300V | Regenerative braking | Motor exclusively powered by battery |

This paper consists of five sections. Section 1 presents research motivations and objectives, and introduces M-HEV technologies at a high level. Section 2 reviews the current market status and third-party forecasts for M-HEVs, and the production cost projection. Section 3 describes the modeling assumptions and approach for the analysis of impacts by the M-HEV technologies using the MA3T model. Section 4 presents scenario analyses for the M-HEV technologies, and gives the market share through 2050 and fleet average fuel economy through 2025 for scenarios impacted by the M-HEV technologies. The simulation results reveal that both the market share and the overall fuel economy vary when the choice positions of M-HEVs in the discrete choice model are changed, which is intended to represent the uncertainty of how consumers may perceive these M-HEVs or how automakers may brand and market M-HEV products. The final section gives the summaries and conclusions.

## 2. Technology Status and Trends

### 2.1. M-HEV technology descriptions

Micro-hybrid vehicles (micro-HEVs) offer a low-cost vehicle option to improve vehicle efficiency, using the stop-start (also interchangeably known as start-stop) technology (Wang et al., 2013). This emerging technology allows the vehicle to entirely turn off the engine when the vehicle is stopped and to immediately turn on engine when the brake pedal is released, or the accelerator pedal is pressed. The adoption of this technology requires the electronic control unit to automatically determine the status of the vehicle and to smoothly turn on/off the engine (Fonseca et al., 2011). Also, it might require frequent use of vehicle starter/engine system. The term micro-hybrid has occasionally been used for a vehicle with regenerative braking (Krithika and Subramani, 2018), but in the context of this study, micro-hybrid technology is synonymous with stop-start ICEV.

Automakers are also transitioning to 48-volt architecture in their ICEVs to further improve fuel economy and performance. These vehicles with 48-volt architecture are usually called mild-HEV. Increasing expectations on comfort, safety, and operation in vehicles have been intensifying light-duty vehicle (LDV) power demands (Delphi Technologies, 2019). To improve the driving experience and powertrain propulsion, the electrified powertrain components are integrated with a conventional internal combustion engine system. As shown in Table 1, two major features of the mild-HEVs are the added 48-volt battery and integrated electric motor/generator. The vehicle can recollect energy through braking and restore it in the propulsion battery after the energy conversion by regenerator. At the same time, the mild-HEV can provide a better acceleration experience with a more powerful electric motor. With

assistance from the electric powertrain components, besides the engine-off at occasional vehicle stops, the vehicle also allows the engine to be turned off for up to 40 seconds while coasting or braking (Gessner, 2018). Therefore, more efficient energy-saving can be achieved by the mild-HEVs than micro-HEVs.

## 2.2.  Historical hybrid vehicle sales

Sales patterns of hybrid vehicles are not uniform worldwide. Higher degrees of hybridization have not been embraced as quickly in the U.S. market as abroad. Since 2008, full hybrid electric vehicles have consistently comprised approximately 2% of the LDV market in the U.S. (Transportation Research Center at Argonne National Laboratory, 2020). According to a report by the China Automotive Technology and Research Center (CATARC), full hybrids achieved 1.21% in the Chinese passenger vehicle market in 2018 (CATARC, 2019). In Japan, full hybrids are very common in the market, being nearly one-quarter of sales in 2014 (Rutherford, 2015). In the European Union, sales of HEV have exceeded 3% since 2017 (ACEA, 2019a, 2019b). The Netherlands have historically had the largest deployment of HEVs, with sales there encouraged by tax incentives (Mock, 2017). Meanwhile, automakers are transitioning to mild-HEVs with 48-volt architecture in their ICEVs to improve performance. So far, only a few vehicles have been equipped with the technology to date, including the Mercedes E-Class and the Audi A8. In brief, the market shares of the hybrid vehicles by country/region are presented in Appendix Table A 1.

The micro-HEV has become popular in markets where idling is emphasized on the official fuel economy testing cycles, in particular in China and Europe. In China, nearly half of new passenger vehicles sold in 2018 have adopted stop-start technology, and most of these cars

are produced by American and European automakers (CATARC, 2019). In the European market,

ICCT finds that stop-start technology has been readily embraced by automakers, and the sales

shares have reached over 70% of light-duty vehicles in 2016 (Mock, 2017). The average growth

rate of micro-HEV technology in the European market was 37% per year between 2001 and

2014 (Wolfram et al., 2016). Discussed by Wolfram et al. 2016, this trend is because of the high

share of idling time on the NEDC (New European Driving Cycle, adopted in both Europe and

China) compared with the U.S. FTP (U.S. Federal Test Procedure) (Wolfram et al., 2016). The

idle time with 294 seconds accounts for 24.9% in the NEDC, while the idle time with 262

seconds, accounting for 19.1% in the FTP and only 0.5% in the highway cycle. By turning off

the engine system entirely when the vehicle is stopped, micro-HEV technology can lower the

fuel consumption and reduce GHG emissions. Clearly, the energy-saving effect of stop-start

technology is more prominent in a driving cycle with more idle time, such as the NEDC, so

deployment of stop-start technologies not only helps vehicle sales but also generate value for

OEMs with respect to more easily meeting stringent fuel economy standards and GHG

requirements. For some manufacturers (e.g., Audi, Mercedes-Benz, BMW, VW, and Renault),

stop-start technology is on the vast majority of their European vehicles, with over 85%

penetration (Wolfram et al., 2016).

Because of the prominent improvement of fuel economy with limited technical redesign

relative to full hybrid vehicles, micro-HEV has become more popular among automakers. In the

U.S., 21% of passenger cars and 36% of light trucks had stop-start engines in 2018, growing

from less than 1% in 2012 (Fact of the Week, 2019; U.S. EPA, 2019), as shown in Figure 1(a).

The growth of stop-start technology in light-duty trucks is much faster than in passenger cars.

This might be because, considering a higher fuel consumption rate in light-duty trucks, the fuel-

saving is more prominent when shutting off the engine for the same amount of time. At the same time, micro-HEV technology is less popular in the vehicle models produced by Japanese and Korean automakers, while it has been more common in the vehicles produced by European and American automakers, as shown in Figure 1(b). This may be because most vehicles produced by the Japanese/Korean automakers are small-sized gasoline engine cars, which have limited room for improving the fuel efficiency through stop-start technology only, or because these Japanese/Korean automakers are meeting fuel economy standards though use of other technologies to improve vehicle fuel efficiency.

On the other hand, stop-start technology could offer more relative benefit on larger, higher-friction engines. The benefit/cost of the hardware is not as justified in a smaller engine where it might give very limited fuel economy improvement. Many vehicles produced by the European and American automakers are either diesel engine vehicles or large-sized light-duty vehicles such as pick-ups and truck-based SUVs, with modest extra cost, the adoption of stop-start technology could largely increase the fuel-saving to improve the CAFE. In these large-sized vehicles, the engine pistons and rings are almost 50% of total engine friction at idle (Ligier and Noel, 2015), so turning off at idle makes a big difference to these vehicles. However, why different automakers have different strategies on the stop-start technology is not yet fully understood.
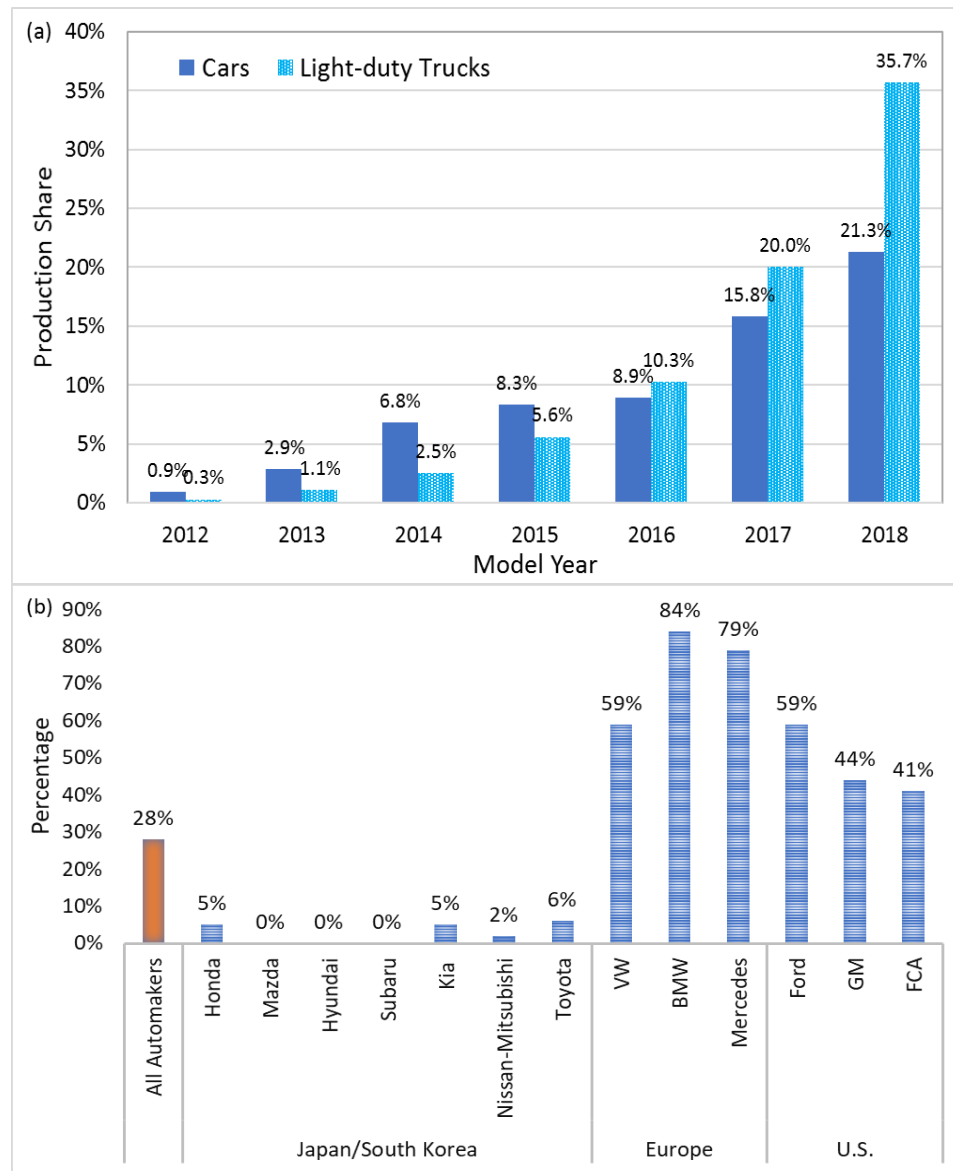
**Figure 1.** (a) Stop-start technology penetration on conventional ICEVs in the U.S., model year 2012-2018 (Fact of the Week, 2019); and (b) automaker use of stop-start technology for model year 2018 (U.S. EPA, 2019).

Though micro-HEV technology is in general very reliable in vehicles and its market penetration is growing, there are still some downsides for this technology. The driving experience might be damped when engine restarting is sluggish (Taub, 2016), and some drivers could feel annoyed when they find their vehicle engines are turned off automatically (Jerew,

2018). Also, because of the frequent turning on/off the engine, this technology requires more-powerful and efficient starters, and the engine also needs auxiliary engine coolant and engine oil pump to maintain pressure and temperature (Jerew, 2018).

### 2.3.    OEM plans and third-party forecasts

For many automakers, the trend toward electrification involves production of both hybridized vehicles propelled by internal combustion engines, and PEVs capable of being powered by electricity from the grid. To this end, several OEMs have announced plans for hybridized vehicles in their fleet. Volvo has shared a plan to have every vehicle model with an electrified option (Marshall, 2017), every Jaguar Land Rover model line will be electrified from 2020 (Vaughan, 2017), Jeep will have electrification options available across each nameplate by 2021 (Lambert, 2018), and Mercedes-Benz plans the same by 2022 (Daimler, 2017). Toyota and PSA Group have announced that all vehicles will have an electrified option by 2025 (Eisenstein, 2018; Lambert, 2017). Ford has announced plans to sell models of hybrid pickup truck, sports car, and police vehicles by 2020 (Ford, 2017).

Sales shares of hybrid vehicles are generally (but not unanimously) expected to grow rapidly in the near future, both domestically and worldwide. Despite the planned growth of all types of electrified vehicles, only a few publicly accessible forecasts do distinguish lower levels of hybridization (e.g. micro-HEV, mild-HEV) from conventional ICEVs. IHS Markit forecasts 22 million mild-HEVs by 2025, over 20% of the global market (Kirwan, 2019). The Boston Consulting Group forecasts 17% of the U.S. market, and 15% of the global market as mild hybrids by 2025 (Mosquet et al., 2018). Frost and Sullivan estimates 8% of the U.S. market and 40% of European market as mild-HEVs by 2025 (Frost and Sullivan, 2018). Less optimistically,

the Annual Energy Outlook (AEO) from the U.S. Energy Information Administration (EIA)

projects that mild-HEVs with integrated starter-generators will comprise under 3% of the U.S.

market by 2025, and still under 4% by 2050 (U.S. Energy Information Administration, 2015).

However, the 2020 AEO does project rapid growth of micro-HEVs to one-quarter of the light-

duty vehicle market by 2025, but then minimal growth after that. Relying heavily on AEO

forecasts for the U.S. market, RBC estimates 3% of the U.S. market and 12% of the global

market to be mild-HEVs by 2025 (Spak et al., 2018). In 2014, Valeo forecasts 3% of the U.S.

market would be mild-HEV in 2020, and 10% of the U.S. market would be mild-HEVs by 2024

(Vint, 2014). In 2016, IDTechEx forecasts 14% of light-duty vehicle sales worldwide would be

mild-HEVs in 2025, growing to 55% by 2030 (Harrop, 2016). The Center for Automotive

Research (CAR) estimates 6% of worldwide sales to be mild-HEVs in 2025, and 10% in 2030

(Bailo et al., 2018).  In the following sections, we present modeling of the U.S. light-duty vehicle

market through 2050 using MA3T to compare with these third-party forecasts of M-HEV

technology penetrations.

## 3.  Approach

In this study, the MA3T model was adopted and adapted for the impact analysis of the

M-HEV technologies in the U.S. light-duty passenger vehicle market. The MA3T model,

developed by the Oak Ridge National Laboratory for the U.S. DOE's Vehicle Technology

Office, is a market simulation tool which adopts the theory of discrete choice to quantify and

project the sales demand for different vehicle technologies by considering relevant attributes of

vehicle technologies, fuel infrastructure, market dynamics, policies and consumer behaviors (Lin

and Greene, 2010) (Liu and Lin, 2016). MA3T estimates the purchase probability by a given

consumer segment for each powertrain technology choice and multiplies these probabilities with

sizes of consumer segments to calculate sales by powertrain choice. Powertrain choices in MA3T

includes 4 vehicle classes (sedan, car-based SUVs, pick-up trucks, and truck-based SUVs), each

of which includes gasoline ICEV, diesel ICEV, full HEV, PHEV, BEV and, for this study,

micro-HEV and mild-HEV. MA3T includes 1,458 consumer segments that represent diverse

demographic attributes of the target population--the U.S. households by driving pattern, home

type, income, technology attitude, and regional incentives. MA3T has been applied in peer-

reviewed studies on fuel economy standards (Xie and Lin, 2017), dynamic wireless charging

(Lin and Li, 2014), hydrogen fuel cell vehicles (Greene et al., 2013), and R&D target evaluation

(Lin et al., 2013). More technical details, calibration and validation of MA3T can be found at

(Liu and Lin, 2016).

This study adapts the MA3T model to estimate the market impacts of M-HEV

technologies. The manufacturing costs, vehicle fuel economy by driving cycle, and driving

attributes such acceleration in the M-HEV are investigated and integrated into MA3T, which

projects sales of various powertrain choices and calculates the resulting fleet-wide sales-

weighted fuel economy through 2050. Figure 2 illustrates a flow chart of such an analysis

approach. The data on the M-HEV manufacturing cost and fuel economy used in the MA3T
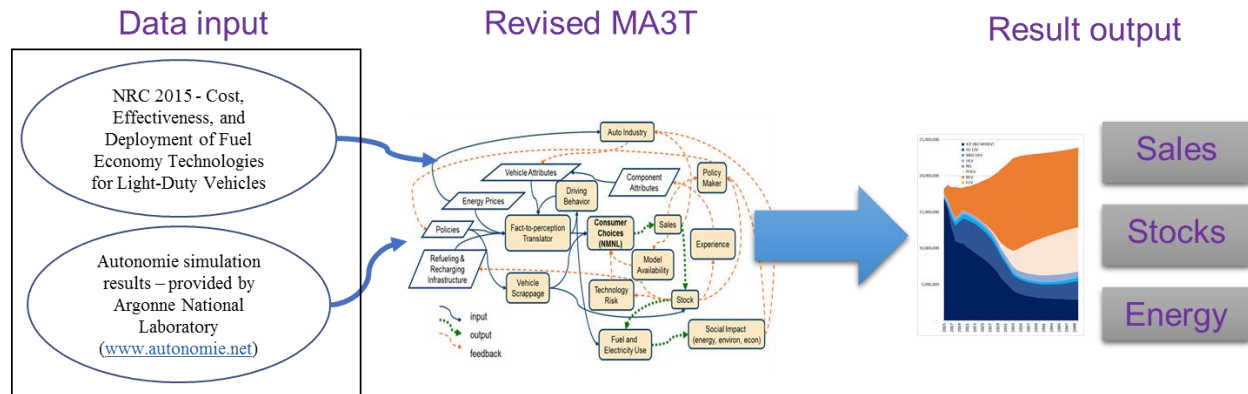
model are described below.



**Figure 2.** The flow chart of MA3T for M-HEV technology analysis (Lin and Greene, 2010).

## 3.1.  Vehicle cost

One way of discerning the cost of hybridization (from a consumer perspective) is to

compare the manufacturer's suggested retail price (MSRP) of the hybrid and of a comparable

conventional ICEV counterpart. Using a comparison tool on www.FuelEconomy.gov, we find

that the average premium of hybridization for model year 2019 vehicles is $1,500, and has been

dropping by approximately $250/year since 2013 (fueleconomy.gov, 2019), as shown in

Appendix B.1. Another way to examine the cost (from the automaker perspective) is to look at

modeling results for conventional and hybridized vehicles. For example, this study used the

results from Autonomie, a vehicle system modeling tool developed by the Argonne National

Laboratory, for comparisons. More analysis on Autonomie results are described in Appendix

B.2. In addition, the estimated manufacturing costs of vehicle hybridization studied by other

literatures are summarized by Appendix B.3.

In general, manufacturing cost is assumed to correlate with the vehicle fuel economy (National Research Council, 2015; Xie et al., 2017), where increased fuel economy comes at an incremental manufacturing cost. To estimate the total manufacturing costs for hybridized vehicles, this study comprehensively considers the analysis by both the National Research Council (NRC) report in 2015 (National Research Council, 2015), and the cost report by Autonomie, which provides manufacturing costs and fuel economy for different M-HEV technologies (Islam et al., 2018). The vehicles modeled in the most recent Autonomie report are technologies representative of the sales market for each class, and include modeling for micro- and mild-HEVs through 2050 (Islam et al., 2018).The extra manufacturing cost of M-HEVs compared to conventional ICEVs in the same vehicle model depends on what fuel-saving technologies are added in the vehicle components. Table 2 summarizes the incremental direct manufacturing costs in different M-HEVs by vehicle class based on an analysis by the NRC (National Research Council, 2015). The incremental direct manufacturing costs are all the values at the price level in the year 2010. CSUV stands for the car-sized SUV, and TSUV stands for the truck-sized SUV. The car described by the NRC report is the midsize car only. The NRC report does not give the manufacturing cost estimation for the TSUV, but considering the similar powertrain size between the pickup and the TSUV, this study assumes that the incremental direct manufacturing costs of M-HEV technology for pickups and TSUVs are the same.

**Table 2.** Projection of M-HEV incremental direct manufacturing cost (2010$) by the NRC report

(National Research Council, 2015)

| Year | M-HEV | Technology | Car | CSUV | Pickup | TSUV |
|---|---|---|---|---|---|---|
| 2017 | Micro-HEV | stop-start (12V) | 287-387 | 325-425 | 356-456 | 356-456 |
| 2017 | Mild-HEV | Integrated Starter Generator | 1374-1640 | 1412-1802 | 1443-1894 | 1443-1894 |
| 2020 | Micro-HEV | stop-start (12V) | 261-336 | 296-371 | 325-400 | 325-400 |
| 2020 | Mild-HEV | Integrated Starter Generator | 1269-1496 | 1304-1645 | 1333-1729 | 1333-1729 |
| 2025 | Micro-HEV | stop-start (12V) | 225-275 | 255-305 | 279-329 | 279-329 |
| 2025 | Mild-HEV | Integrated Starter Generator | 1113-1293 | 1113-1420 | 1167-1493 | 1167-1493 |

We combine the conventional ICEVs modeled in Autonomie with the marginal cost information presented in the NRC report to obtain the manufacturing costs for M-HEV technologies as shown in Figure 3. All the cost numbers are adjusted based on inflation to the price level in 2010. The manufacturing cost of micro-HEVs is quite close to the manufacturing cost of conventional vehicles, between 1–3% higher. The extra manufacturing costs of both micro-HEV and mild-HEV generally decrease over time due to technology improvement. The manufacturing cost of M-HEV technologies remains lower than HEV. At last, the vehicle price is the manufacturing cost multiplied by the mark-up factor which is calibrated based on historical prices and sales data.
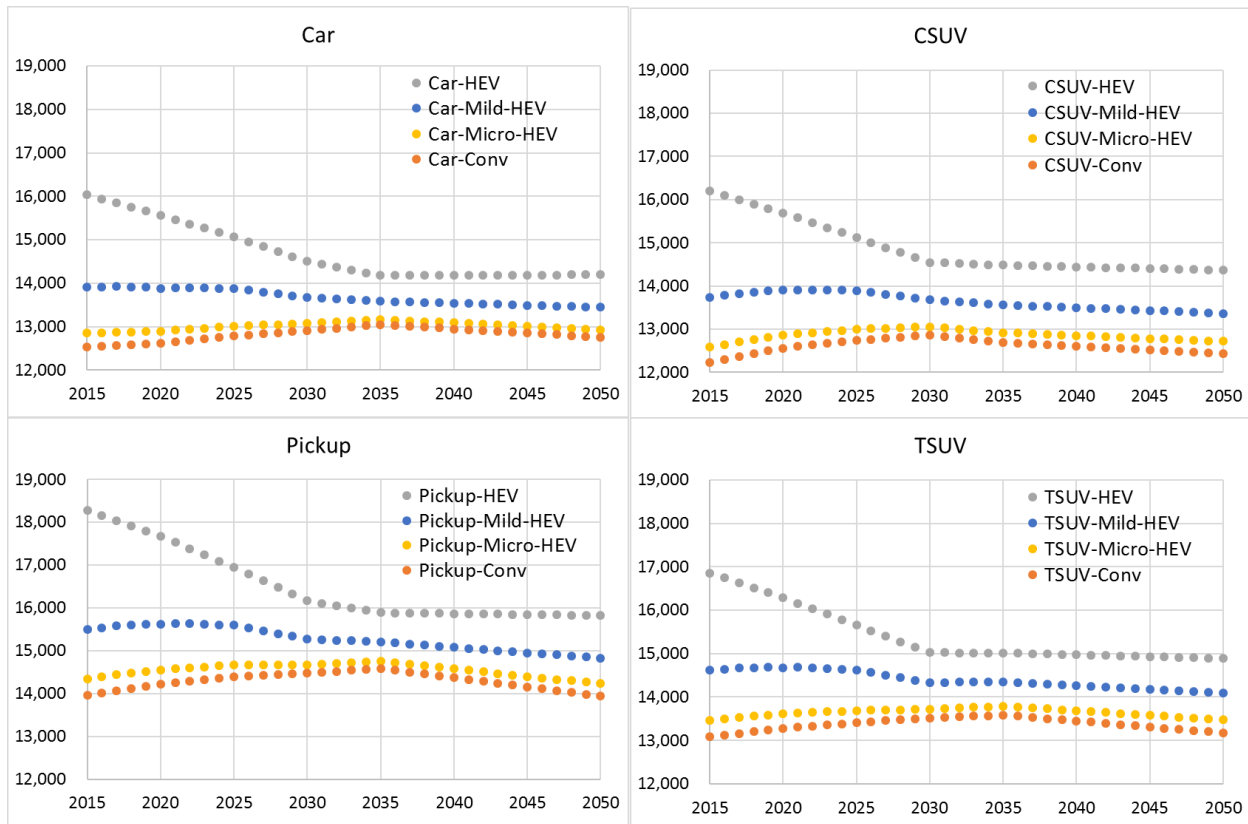
**Figure 3.** Estimation of M-HEV manufacturing costs based on NRC report and Autonomie (costs in 2010$).

## 3.2. Fuel economy

The estimate of the fuel economy improvement due to M-HEV technology is also based on simulation results by Autonomie model and the NRC report (National Research Council, 2015; Xie et al., 2017). Table 3 shows the estimated fuel consumption reduction effectiveness of M-HEV technologies, relative to conventional ICEVs, from the NRC Report (National Research Council, 2015). Autonomie also provides the fuel economy projections of conventional and M-HEV technologies in future years, estimated under the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) test cycles. Usually the fuel saving for hybrid technologies is more effective in the UDDS driving cycle, because driving conditions such as idling and changes in acceleration are more frequent in the UDDS, allowing greater

impacts of stop-start or braking regenerative technologies. The Autonomie estimates show the

fuel consumption reduction in UDDS by about 6–7.5% for micro-HEVs and 12–15% for mild-

HEVs; and in HWFET by about 0.3–2.2% for micro-HEVs and 3.1–4.9% for mild-HEVs. If the

ratio of UDDS to HWFET is 43% to 57%, representative of real-world driving according to the

EPA (U.S. EPA, 2019), the combined fuel consumption reduction is about 3.6–5.5% for micro-

HEVs and about 9.0–10.5% for mild-HEVs. The Autonomie estimates of fuel economy are close

to those in the NRC report. Thus, this study adopts the values from the Autonomie simulation for

the fuel economy for micro- and mild-HEVs, due to more diversity of vehicle types in

Autonomie.

**Table 3**  Estimated Fuel Consumption Reduction Effectiveness of M-HEV Technologies in the NRC

Report (National Research Council, 2015)

| M-HEV | Technology | Car | CSUV | Pickup | TSUV |
|-------|-----------|-----|------|--------|------|
| Micro-HEV | stop-start (12V) | 2.1% | 2.2% | 2.1% | 2.1% |
| Mild-HEV | Integrated Starter Generator | 8.6% | 8.6% | 5.1% | 5.1% |

### 3.3.    Choice positions of M-HEV in model

The micro-HEVs and mild-HEVs might be technically similar; however, from a market

perspective, automakers and consumers might not view a powertrain technology in the same

way. The micro-HEV and the mild-HEV could be marketed by automakers as closer to

conventional ICEVs or closer to full HEVs. Whether their marketing or branding strategy will

successfully convince consumers have implications on how these technologies should be

represented in the choice structure of this study. The MA3T model, adopted in this study, is a

discrete choice model which can simulate the consumer behavior and consider the perception of

vehicle technologies. The positions of the M-HEVs in the choice structure could affect the

estimated adoption of the technology. It is a consumer perception/behavior issue that really does

not have a single correct perspective or answer. Until we can be certain about how M-HEV will

be branded by OEMs and perceived by consumers, the uncertainty should be addressed. One

approach is to place M-HEVs in different, reasonable positions in the choice structure and

evaluate the robustness of the conclusion on the impact on PEV sales and fleetwide fuel

economy.

Considering no substantial information is found to support which market segment the

M-HEV belongs to, this study revises the structure of the MA3T for considering three different

choice positions of the M-HEV technology scenarios and one scenario in which M-HEV

technology is intentionally not included for impact comparison purposes, as presented by Figure

4. The descriptions of the four scenarios are shown below. The scenario (a) is adopted as a base

case.

- Scenario (a) – base case or "Separated": The two types of M-HEV are placed separately,

  with micro-HEV in the conventional ICEV choice nest, and mild-HEV in the full hybrid

  vehicle nest. As shown in Table 1 and Figure 3, the components and manufacturing costs

  of micro-HEV are not much different from the comparable conventional ICEV model,

  and the fuel consumption reduction is about 3%, so it seems reasonable to regard the

  micro-HEV as a conventional ICEV. The stop-start technology can be viewed as an

  option or new feature of a conventional ICEV. Many more fuel-saving components are

  added into the mild-HEV, and more important, the battery in the mild-HEV can also

  partially work for vehicle propulsion and recycle the energy from the braking system, so

from the engineering perspective, mild-HEVs are more similar to a full hybrid vehicle.

Thus, the mild-HEV is assigned to the hybrid vehicle segment in this scenario.

- Scenario (b) – "Both in ICEV": Both the micro-HEV and the mild-HEV are placed in the conventional ICEV nest. This modeling approach represents the possibility that both micro-HEV and mild-HEV are branded as conventional ICEVs. This is possible because most M-HEV models released by OEMs are upgrades of existing vehicle models so to meet the stricter CAFE standards, rather than new designs. Plus, except for the powertrain technology difference, these M-HEV products are largely the same as their original ICEV products.

- Scenario (c) – "Both in HEV": Both the micro-HEV and the mild-HEV are positioned within the hybrid vehicle choice nest. This scenario represents the possibility that OEMs promote M-HEV as a more cost-effective alternative to full HEVs and keep the conventional ICEVs as a distinct technology category.

- Scenario (d) – "No M-HEV": M-HEV is not explicitly included as if the M-HEV technology does not exist. This scenario is constructed to provide a comparison reference in order to evaluate the impact of M-HEV technology in other scenarios.
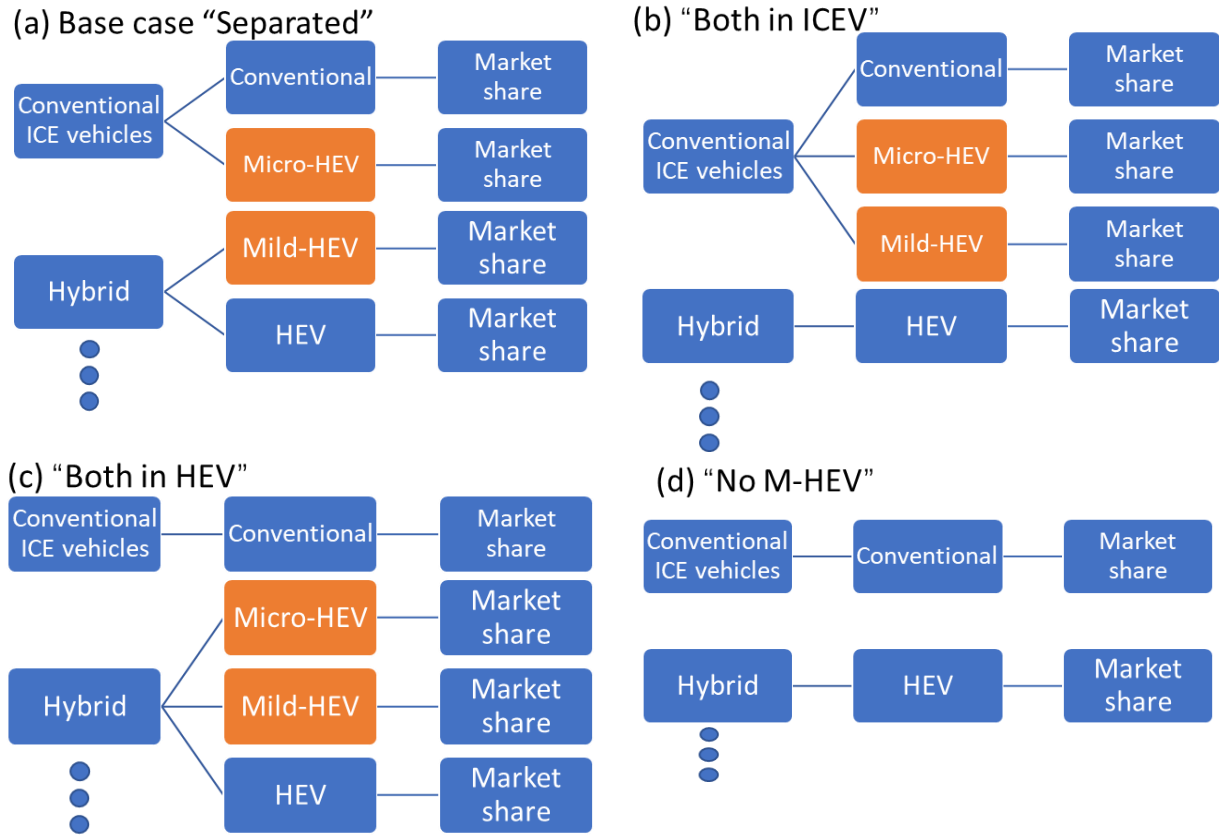
**Figure 4.** The choice positions of the M-HEV technology in the MA3T model.

## 4.   Results and discussion

### 4.1.   Market shares

This study aims to quantify the potential impacts of the micro/mild hybrid technology (M-HEV) on the sales shares of powertrain technologies and fleetwide average fuel economy. Projected sales shares of different powertrain technologies for the 4 scenarios as in Figure 4 are shown in Figure 5.

The projected market share of M-HEV technology varies as the M-HEV technologies are positioned differently in the choice structure as in Figure 4. Overall, it appears that M-HEV is most successful in scenario (a) "Separated". This is logical because when the two M-HEV types

can each compete against ICEV and HEV directly without competing with each other, the market strength of M-HEV can be maximized. In either the "Both in ICEV" or "Both in HEV" scenarios, micro-HEV and mild-HEV compete against ICEV or HEV but also against each other, and therefore the M-HEV total sales share is suppressed to some extent. It also appears that micro-HEV is more attractive than mild-HEV when they are in the same choice nest.

But regardless of the choice position, the M-HEV technology is estimated to gain significant market shares from conventional ICEVs and full HEVs, based on comparison between each of scenarios (a) "Separated", (b) "Both in ICEV", (c) "Both in HEV" to scenario (d) "No M-HEV". Meanwhile, PHEV and BEV market shares are largely unaffected by the presence and choice position of M-HEV. If M-HEV is viewed as another efficiency technology in the "ICEV+HEV" category, this means that M-HEV's cost-effectiveness is good enough to impact sales of ICEVs and full hybrid vehicles, but not good enough to affect PEV sales. From the policy perspective of promoting both electrification and efficiency, this is important.
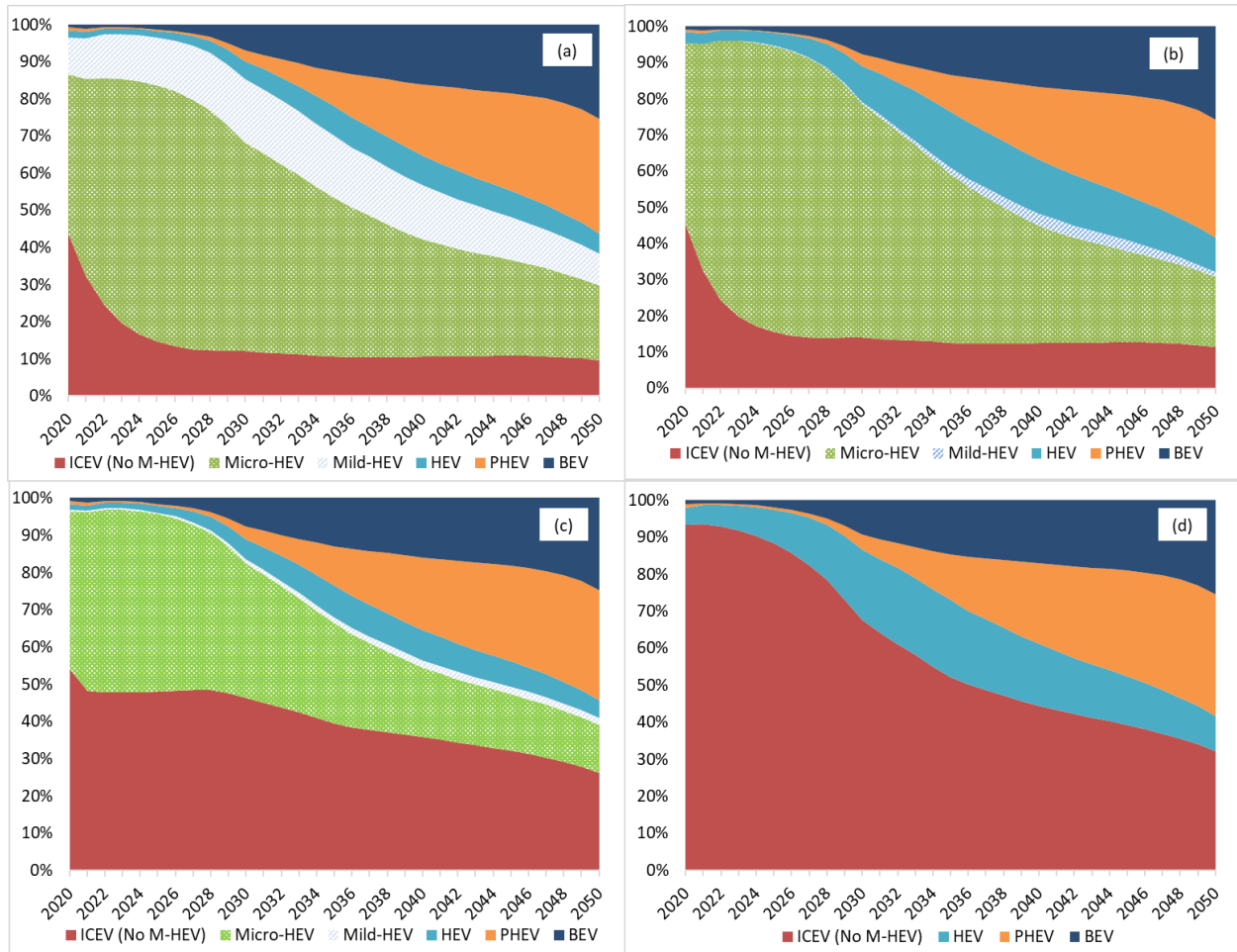
**Figure 5.** Projection of the vehicle market share by the MA3T model: (a) "Separated"; (b) "Both in ICEV"; (c) "Both in HEV"; (d) "No M-HEV".

However, which of ICEVs and HEVs lose more sales shares to M-HEV does depend on the choice positions of micro-HEV and mild-HEV. Conventional ICEVs appear to face a great challenge from the M-HEVs, in all cases, especially in Scenario (a) "Separated" and (b) "Both in ICEV", where at least one type of M-HEV directly competes with conventional ICEVs. This fundamentally is because M-HEVs are substantially more fuel-efficient with only a modest increase of manufacturing costs. In Scenario (c) "Both in HEV", the choice nest of HEV is strengthened by having the two M-HEV types and thus cause conventional ICEVs to lose shares. For HEVs, M-HEV creates significant competition pressure as long as mild-HEV or both M-

HEV types are in the same choice nest as HEV. In Scenario (b) "Both in ICEV", HEV sales remain largely unaffected compared to Scenario (d) "No M-HEV".

In the short term (before year 2025), the M-HEVs are projected to quickly gain shares and slightly slow down the PEV market growth. Meanwhile, sales of M-HEVs are contributed mostly by the micro-HEVs rather than mild-HEV, no matter how the two M-HEV types are positioned in the choice structure. Overall, through 2025, the projected market shares for mild-HEV are within the ranges of forecasts published by others as presented in Section 2.3.

When it comes to the long term (after year 2025), in all four scenarios, the PEV sales shares are projected to grow in the same pattern and magnitude, indicating little impact by M-HEV on PEV sales. Growth in PEV sales is mainly driven by gradual reduction of battery cost and expansion of charging infrastructure. The BEV sales share is projected to grow from about 2% by 2025 to about 26% by 2050. PEVs are projected to make up about 30% of the market by 2050.

The M-HEV sales share over LDVs appears to peak around 2030 by mainly squeezing conventional ICEVs and full hybrid vehicles, depending on M-HEV's choice positions. The decline of the M-HEV sales shares over LDVs is due to the competition from PEVs. However, the pressure of PEV competition is on both ICEV and HEV choice nests as in Figure 4, not specifically on M-HEV. In fact, the relative market share of M-HEV against conventional ICEVs and full hybrid vehicles remain relatively stable after 2030.

In summary, M-HEV does not threaten PEVs. Outside PEVs, micro-HEVs appear to be most competitive with respect to cost-effectiveness on fuel economy improvement, followed by ICEV, mild-HEV and then full HEV.

### 4.2. Fleetwide average fuel economy

To evaluate the extent to which the M-HEV technology can improve energy efficiency, this study calculates the fleetwide sales-weighted average fuel economy under the four scenarios (a-d) from year 2020 to year 2025. The calculation will exclude PEVs for simplicity, for highlighting internal combustion engine-based vehicles (ICEVs, M-HEVs and HEVs) efficiency improvement, and for the observation that PEV sales shares are almost identical among the four scenarios (Figure 5). As shown in Figure 6, the rapid market share growth of the M-HEVs can improve the fleetwide average fuel economy. As previously analyzed, the market penetration of M-HEVs mainly affects sales shares of ICEV and HEV. When M-HEVs replace HEVs, the fleetwide fuel economy is actually reduced, because a HEV has a higher fuel economy than a M-HEV. It is the replacement of ICEVs by M-HEVs that results in fuel economy improvement. Overall, comparing scenarios (a), (b), (c) with scenario (d), M-HEVs raises the fleetwide fuel economy by 0.2-0.6 MPG during 2019-2025, which is equivalent to reducing fuel consumption rate by 0.7%-1.9%.
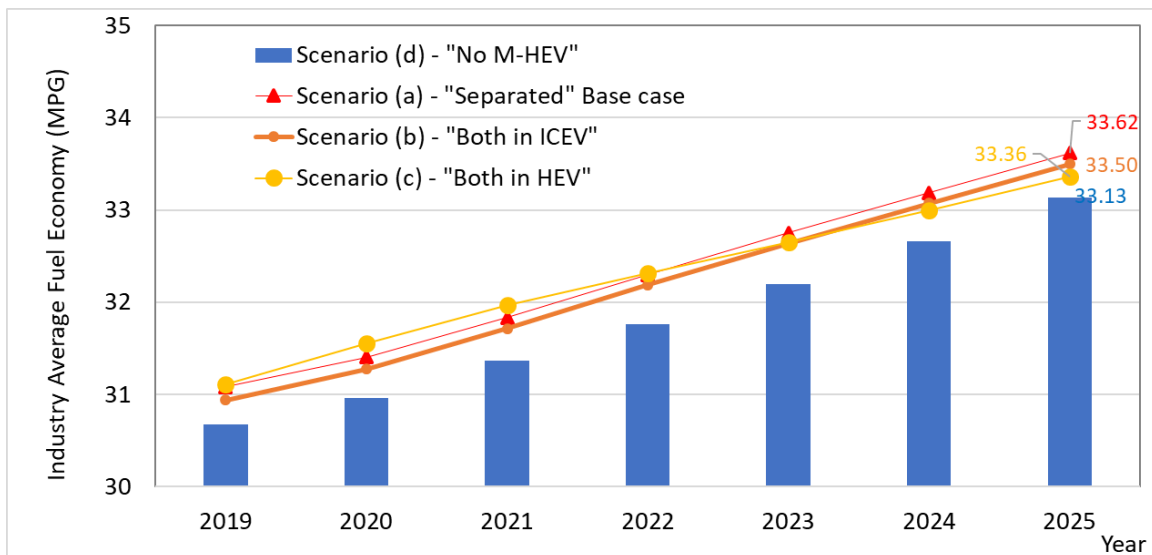


**Figure 6.** Comparison of fleetwide average fuel economy in scenarios.

## 4.3. Sensitivity analysis

Sales shares of M-HEVs can be affected by factors of own competitiveness such as the manufacturing cost of M-HEV, as well as by factors of competing choices, such as BEV price. A sensitivity analysis is conducted on three parameters – incremental price of micro/mild-HEVs respectively, incremental fuel consumption of micro/mild-HEVs, gasoline price and BEV price. Scenario (a) "Separated" is used as the base case for sensitivity analysis. The market shares of micro/mild-HEVs are simulated with one of the above three parameters increased or decreased by 20% from its value in the base case. The incremental fuel consumption is the difference between the fuel consumption of micro/mild-HEVs and the fuel consumption of comparable conventional ICEVs. Similarly, the incremental price is the difference between the price of micro/mild-HEVs and the price of comparable conventional ICEVs. The fuel consumptions and prices after $\pm 20\%$ change of incremental fuel consumption and incremental price in micro/mild-HEVs are presented by Eqn. (1-4).

$$FC_{M-HEV+20\%} = FC_{M-HEV} + 20\% \cdot |FC_{M-HEV} - FC_{ICE}| \tag{1}$$

$$FC_{M-HEV-20\%} = FC_{M-HEV} - 20\% \cdot |FC_{M-HEV} - FC_{ICE}| \tag{2}$$

$$P_{M-HEV+20\%} = P_{M-HEV} + 20\% \cdot |P_{M-HEV} - P_{ICE}| \tag{3}$$

$$P_{M-HEV-20\%} = P_{M-HEV} - 20\% \cdot |P_{M-HEV} - P_{ICE}| \tag{4}$$

where $FC$ is the fuel consumption, and $P$ is the vehicle price.

Figure 7 (a) and (b) present the relative changes of micro/mild-HEV market shares in year 2025 impacted by the parameters discussed. The relative changes of micro/mild-HEV market shares are denoted by Eqn. (5).

$$\Delta MS = \frac{MS_{\pm 20\%} - MS_{base\ case}}{MS_{base\ case}} \tag{5}$$

where $\Delta MS$ is the relative change of market share (%), $MS_{\pm 20\%}$ is the market share of

micro/mild-HEVs after parameter's 20% change (relative increase or relative decrease), and

$MS_{base\ case}$ is the market share of micro/mild-HEVs in the base case.

Comparing the results shown in Figure 7, in general, the market share of M-HEV

(including both micro-HEV and mild-HEV) is more sensitive to the decrease of BEV price than

it is to the increase of BEV price. This might be because the BEVs can substitute the M-HEV

easily if BEV price becomes more competitive and the fuel-saving advantage of M-HEV is not

so distinctive in the vehicle market. After all, the M-HEVs are commonly regarded as a fuel-

efficient upgrade for conventional ICEVs or simplified HEVs. This finding also reflects why the

M-HEV can be highly popular in the vehicle market currently dominated by the ICEV: The M-

HEV improves the fuel economy without prominent extra increase of cost.

Though both micro-HEV and mild-HEV are regarded as competitive substitutes for

ICEVs, sensitivity analysis on gasoline price reveals different trends in consumer acceptance on

fuel-saving. When the gasoline price relatively increases by 20%, the share of micro-HEV

decreases while mild-HEV increases. This is caused by their different positions in the structure

choices and relative capabilities to reduce fuel costs. More like ICEV, the micro-HEV costs more

on gasoline than mild-HEV, HEV and PEV, because of its limited fuel-saving when gasoline

price increases; conversely, the mild-HEV can relatively save more on fuel costs and could have

a less drop-off or even an increase on market share when gasoline price increases. Meanwhile,

compared to the share of M-HEV which has smaller relative changes between -4 and 3%, the

market shares of PEV, HEV and ICEV are more susceptible to the gasoline price. For example,

when the gasoline price relatively increases by 20%, the share of ICEV relatively decreases by

4% while the share of BEV relatively increases by more than 60%. In addition, the differences

can also be clued through the sensitivity analyses on the factors – the incremental fuel

consumption and the incremental vehicle price: the market share of mild-HEVs is more impacted

by a 20% change of the incremental fuel consumption or the incremental vehicle price compared
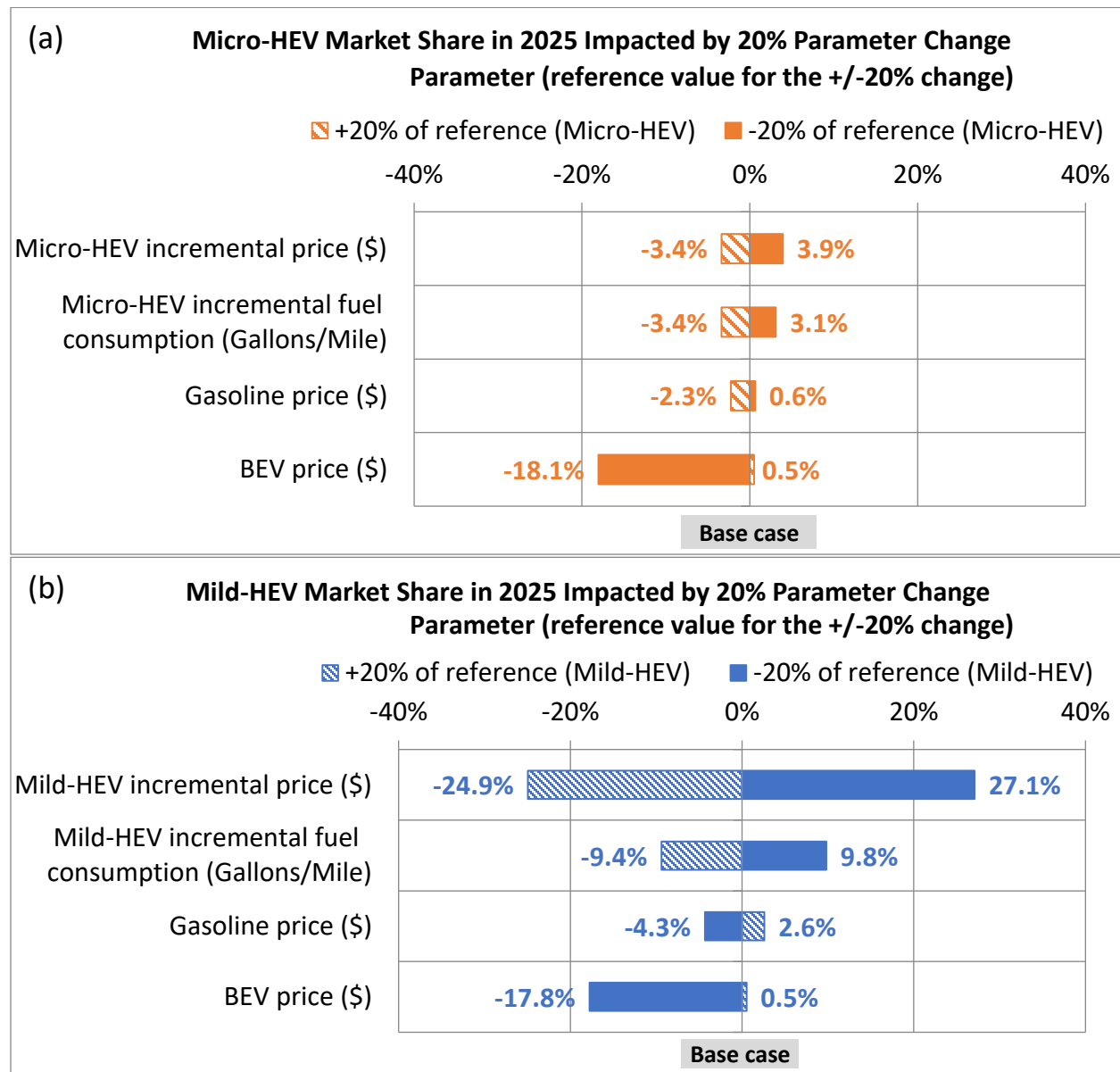
to the market share of micro-HEVs.

**(a)** **Micro-HEV Market Share in 2025 Impacted by 20% Parameter Change**
**Parameter (reference value for the +/-20% change)**

⊠ +20% of reference (Micro-HEV)    ■ -20% of reference (Micro-HEV)

Micro-HEV incremental price ($): -3.4% / 3.9%

Micro-HEV incremental fuel consumption (Gallons/Mile): -3.4% / 3.1%

Gasoline price ($): -2.3% / 0.6%

BEV price ($): -18.1% / 0.5%

Base case

**(b)** **Mild-HEV Market Share in 2025 Impacted by 20% Parameter Change**
**Parameter (reference value for the +/-20% change)**

⊠ +20% of reference (Mild-HEV)    ■ -20% of reference (Mild-HEV)

Mild-HEV incremental price ($): -24.9% / 27.1%

Mild-HEV incremental fuel consumption (Gallons/Mile): -9.4% / 9.8%

Gasoline price ($): -4.3% / 2.6%

BEV price ($): -17.8% / 0.5%

Base case

**Figure 7.** Sensitivity analysis: (a) micro-HEV technology share in the vehicle market in 2025; and (b)

mild-HEV technology share in the vehicle market in 2025.

## 5.  Conclusions

This paper aims to evaluate the fleetwide impacts of the M-HEV technology (micro-HEVs and mild-HEVs) on the vehicle market in the U.S. from the perspective of vehicle sales and fleetwide average fuel economy. We review the market development of fuel-saving and highly efficient powertrain technologies in recent years, analyze the market influence of the M-HEV technology with a quantitative simulation tool – MA3T model, and project the future vehicle sales and share of M-HEV technology by 2050. According to the literature review done through this study, we find that the M-HEV technology such as stop-start, 48-volt architecture, and affiliated electrified powertrain components have been commonly adopted in many new vehicle models by mainstream automakers. This might be because the upgrades can effectively improve the vehicle fuel economy with limited extra costs on the basis of the current ICEV powertrain system. Besides, by investigating the impacts of the M-HEV technology in the vehicle market through modeling and simulation, this paper presents the insights that are expected to inform stakeholders involved with the U.S. vehicle market:

1)  The simulation results show that M-HEVs are likely to dominate the engine-based powertrain market in the next decades. Outside PEVs, micro-HEVs appear to be most competitive, followed by ICEVs, mild-HEVs and then full HEVs.

2)  In the short term (before year 2025), the M-HEV is projected to quickly gain shares and could slightly slow down the PEV market growth. However, in the long-term (after year 2025), M-HEVs seem to have limited adverse effects on market growth of PEVs.

3) As the M-HEV market grows during 2019-2025, the industry fleetwide fuel economy in conventional internal combustion engine-based vehicles increases by 0.2-0.6 MPG, or the equivalent fleetwide fuel consumption decreases by 0.7%-1.9%.

4) The capability of M-HEVs to improve vehicle fuel economy with fewer extra costs might be a major reason for the rapid market penetration of the M-HEVs.

The contribution in this study is to create a framework for investigating new advanced vehicle technology from its manufacturing cost, fuel economy and potential impacts on the vehicle market through utilizing the quantitative modeling tool. Currently, some assumptions such as the projections of the fuel economy are based on literature, and some calculations are reasonably simplified for quantitative modeling. As more is learnt about the data and the market, the analysis and the model will be updated and improved.

## 6.  Acknowledgments

## 7.  Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Z. Lin, D. Gohlke, S. Ou,; data collection: Z. Lin, S. Ou, D. Gohlke; analysis and interpretation of results: Z. Lin, S. Ou, D. Gohlke; draft manuscript preparation: S. Ou, D. Gohlke, Z. Lin. All authors reviewed the results and approved the final version of the manuscript.

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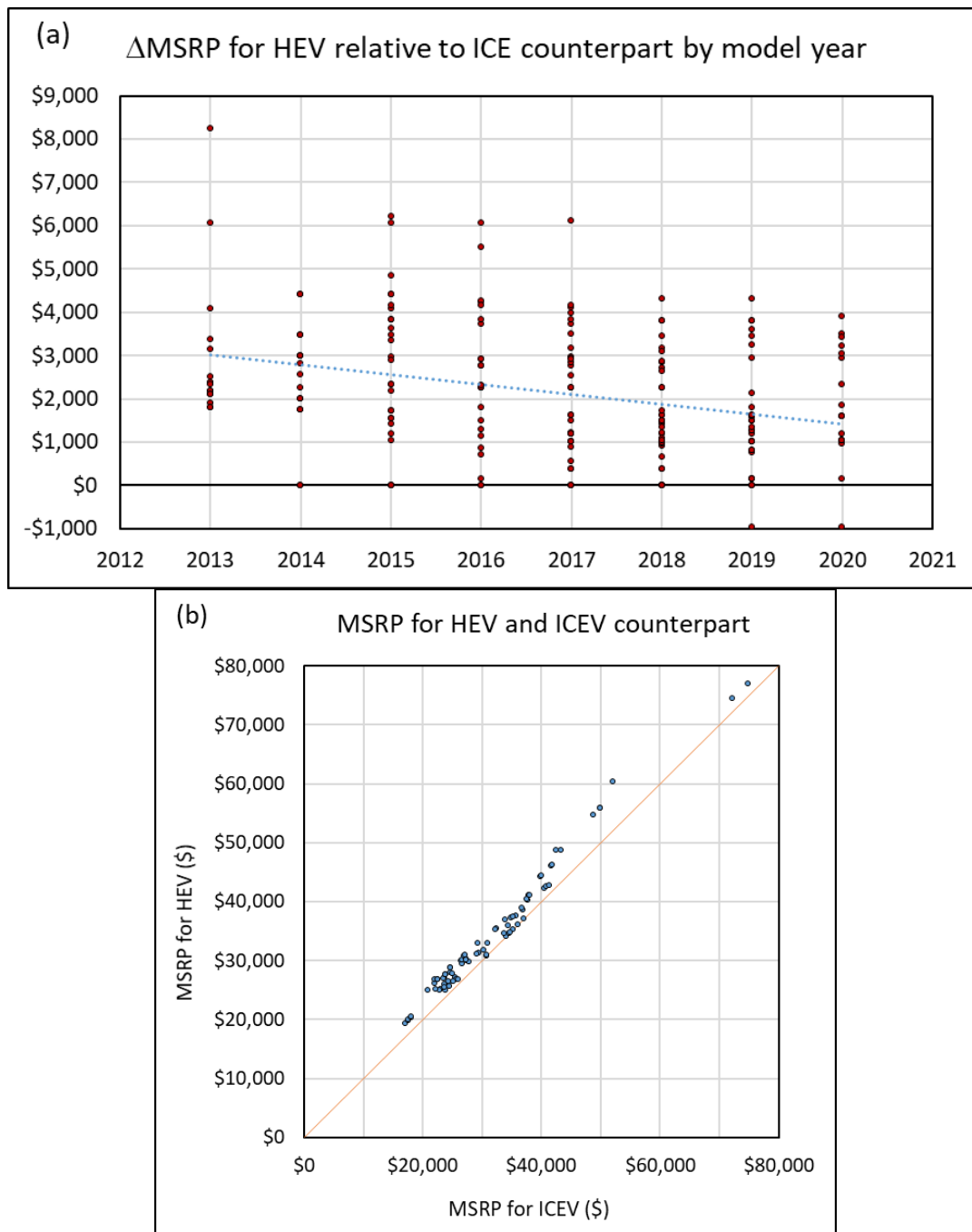
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# Appendix A

**Table A 1 Shares of hybrid vehicles in light-duty vehicle market by country/region**

| Country | HEV share [year] | Micro-HEV share [year] |
|---------|------------------|------------------------|
| China | 1.21% [2018] (CATARC, 2019) | ~50% [2018] (CATARC, 2019) |
| European Union | >3% [2017] (ACEA, 2019a, 2019b) | >70% [2016] (Mock, 2017) |
| Japan | 25% [2014] (Rutherford, 2015) | |
| U.S. | 2% [2018] (Transportation Research Center at Argonne National Laboratory, 2020) | 21% in cars, 36% in light-duty trucks [2018] (Fact of the Week, 2019) |

# Appendix B

## B.1. Comparison of MSRPs for HEVs and their ICE counterparts
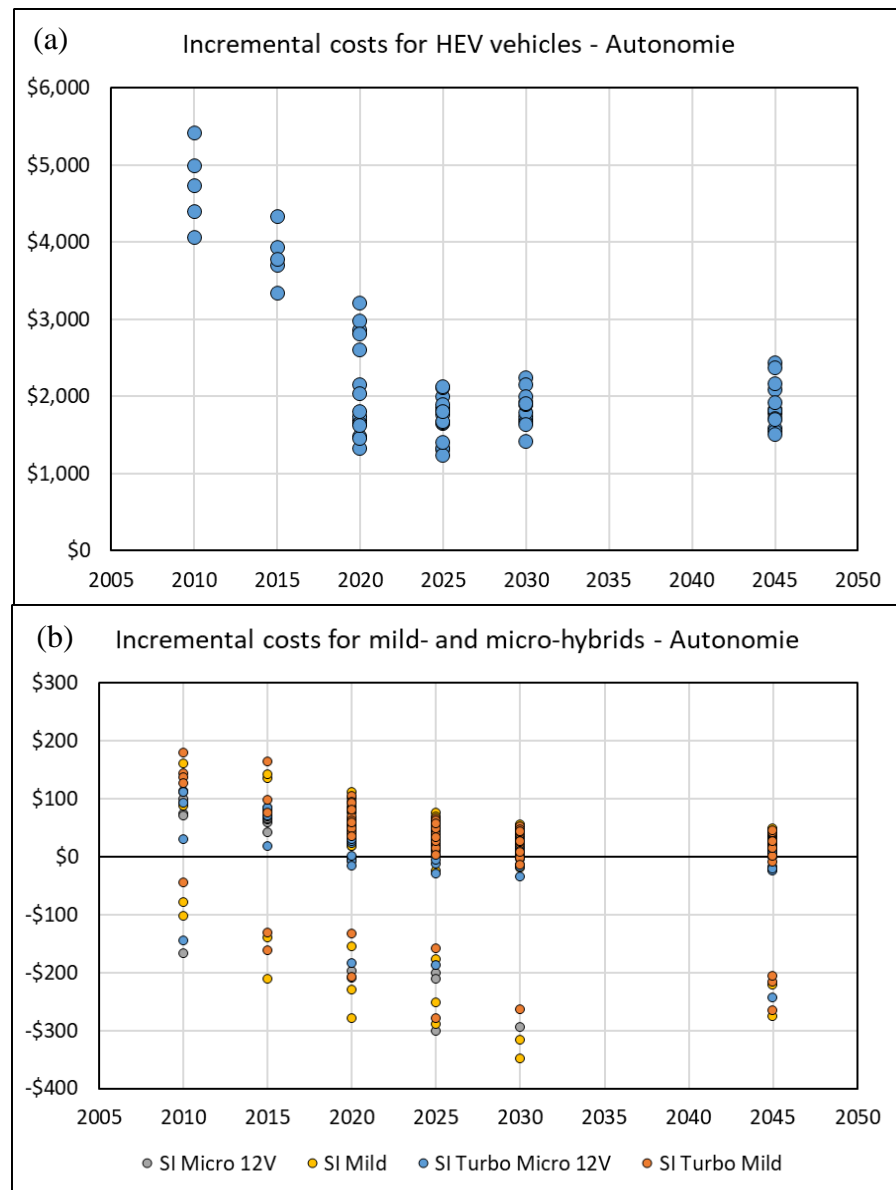


**Appendix Figure B 1.** (a) Comparison of ΔMSRP for HEV and their ICEV counterparts (blue dash line is the average value); and (b) comparison of MSRP for HEV and ICEV counterpart in model year 2012-2020. (Dollars are not inflation adjusted) Data source: www.FuelEconomy.gov, 2019 (fueleconomy.gov, 2019).

**B.2. Incremental costs of M-HEV from Autonomie**

Autonomie is a vehicle system modeling tool developed by the Argonne National

Laboratory. Its results from the most recent U.S. Department of Energy Vehicle Technology

Office/Fuel Cell Technology Office benefits analysis (Islam et al., 2018) are shown in Appendix

Figure B 2**Error! Reference source not found.** (a) and (b). It **Error! Reference source not**

**found.**shows the incremental manufacturing cost of full hybrid vehicles relative to a

conventional ICEV of the same size and performance. Because this is the manufacturing cost, it

is typical to multiply these costs by a factor of 1.5 to derive a retail price equivalent (Rogozhin et

al., 2009). Also, the years on the horizontal axis are lab years; it is typical to assume that these

technologies will be available to consumers 5 years hence (Stephens et al., 2017). The modeled

incremental costs in Autonomie are higher than the MSRP comparisons in Appendix Figure B 1.

This discrepancy may be because of the modeling constraints in Autonomie to have higher

acceleration than some HEVs available today, or due to pricing strategies by the automakers to

encourage hybrid vehicle sales, or due to Autonomie simulating only the most popular vehicle

models in the market.

Appendix Figure B 2(b) shows the difference in incremental costs for mild-HEVs and

micro-HEVs as modeled by Autonomie. As before, these are manufacturing costs and lab years.

In some cases, the incremental cost of hybridization is negative in the Autonomie modeling, that

is, the mild- and micro-HEVs are occasionally cheaper than their ICEV counterparts. This

appears to be because the power from the integrated traction drive is sufficient to allow for the

engine to be downsized while obtaining the same performance requirements. For mild-HEVs, the

10 kW system allows an average downsizing of conventional spark-ignition (gasoline) engines

by 16 kW, which leads to engines with a base cost $76 cheaper, partially offsetting the extra cost

of the integrated starter/generator (Islam et al., 2018). However, for specific vehicles (e.g., 2025

mild-HEV), downsizing of M-HEVs also includes reducing the number of engine cylinders,

causing the hybridized engine to have a negative marginal cost. In other words, this feature of the

modeling could bring the manufacturing cost of a micro-HEV lower than the manufacturing cost

of a comparable conventional ICEV. Although this change might be reasonable in the real

vehicle market, it distorts the quantification of vehicle ownership cost on the new vehicle

technologies in MA3T. Therefore, the vehicle manufacturing costs for M-HEV from the

Autonomie need some revisions before they are incorporated into MA3T.

**Appendix Figure B 2.** (a) Autonomie-modeled comparison of incremental costs (2010$) for full hybrid vehicles relative to conventional gasoline-fueled spark-ignition ICEVs; and (b) Autonomie-modeled comparison of incremental costs (2010$) for mild and micro hybrid vehicles, relative to conventional gasoline-fueled spark-ignition ICEVs.

**B.3. Other estimates on manufacturing costs of vehicle hybridization**

ICCT has estimated manufacturing costs of different levels of hybridization (German, 2015). Both the costs of full HEVs and mild-HEVs, respectively, continue to drop in the near future. The estimated incremental manufacturing cost for mild-HEVs decreases from $1100 in 2017 to $700 in 2025. Full hybrids drop from around $2000 to $1400 in the same timeframe. Other cost estimates come from news articles: Delphi Technologies has gone on the record estimating that 48-volt mild-HEVs typically cost an automaker between $600 and $1,200 (Tracy, 2017). Schaeffler made a demonstration model in 2015 at $750 (Markus, 2015). Johnson Controls made earlier estimates of the incremental cost as $1,000-$1,500 (PowerPulse, 2013). At this price point, the vehicle is comparable in cost to a diesel-powered vehicle, while still being between €500 and €1000 cheaper (Frost, 2017). Incremental costs for stop-start technology are smaller than for mild- and full-hybrid technologies. Xie et al. performed a retrospective meta-analysis to see how cost and efficiency forecasts of these vehicles compared with actual values (Xie et al., 2017). This paper found that cost forecasts for micro-hybrids were $433-$659 in 2011, while forecasts from 2015 predicted an incremental cost of $337-$406.