Abstract
Optimal energy management of hybrid electric vehicles has previously been shown to increase fuel economy (FE) by approximately 20% thus reducing dependence on foreign oil, reducing greenhouse gas (GHG) emissions, and reducing Carbon Monoxide (CO) and Mono Nitrogen Oxide (NOx) emissions. This demonstrated FE increase is a critical technology to be implemented in the real world as Hybrid Electric Vehicles (HEVs) rise in production and consumer popularity. This review identifies two research gaps preventing optimal energy management of hybrid electric vehicles from being implemented in the real world: sensor and signal technology and prediction scope and error impacts. Sensor and signal technology is required for the vehicle to understand and respond to its environment; information such as chosen route, speed limit, stop light locations, traffic, and weather needs to be communicated to the vehicle. Since optimal control requires accurate prediction of the vehicle environment and drive cycle, prediction scope and error impact analysis is needed to understand the required accuracy of sensor and signal information received by the vehicle as well as the accuracy of the optimal control computed. This review presents the current state of research and solutions in development for each of these research gaps. Once these research gaps have been filled, HEVs may have the potential to substantially increase the FE standard and remove ICE vehicles as the leading consumer of petroleum and leading contributor of GHG, CO, and NOx emissions.

Introduction
The background for this research stems from three topics: (1) increasing FE is important, (2) HEVs are a relevant vehicle architecture for the near term future, and (3) optimal energy management can increase HEV FE significantly above the current standard.

Why FE Matters
Historically, due to improved and expanded roads and the invention of the electric starter, consumers have preferred the long range and high speed providing internal combustion engine (ICE) vehicles while alternatives have only been popular during fuel shortages and environmental crises that lead to increased oil and gas prices [1]. Additionally, according to several future outlooks [2, 3, 4] the momentum of ICE powered vehicle will continue until 2040, where the majority of vehicles in the US will continue to be ICE powered, either in conventional or hybrid configurations.

ICE powered automobiles such as light vehicles, buses, medium trucks, and heavy trucks have three major drawbacks: they account for 60.7% of petroleum consumption, 28.2% of greenhouse gas (GHG) carbon emissions, and 32.9% and 36.2% of carbon monoxide and nitrogen oxide emissions (2013 U.S. numbers), all of which are the highest compared to any other sector [5], shown in figure 1.
Reducing petroleum consumption is important because, in 2013, the U.S. was forced to import 38.7% of the petroleum that it consumed since light, medium, and heavy duty vehicles alone consumed 94.4% of the U.S. produced petroleum. This forced oil dependence cost $200 billion dollars to the U.S. economy in the form of wealth transfer, dislocation losses, and from loss of potential GDP in 2013 [5]. Reducing petroleum consumption is important because it would result in recuperation of funds to the U.S. economy, prevent a potential disruption in supply or a spike in cost, reduce the Organization of Petroleum Exporting Countries (OPEC) market power, reduce U.S. military expenditures, and reduce foreign policy effects [6].

Reducing GHG emissions is important because it would reduce the significant risks already affecting a broad range of human and natural systems. Most of the 1.4 °F increase in the planet’s average surface temperature over the last hundred years can be attributed to GHG emissions. Negative effects of global warming include increases in the frequency of intense rainfall, decreases in Northern Hemisphere snow cover and Arctic sea ice, warmer and more frequent hot days and nights, rising sea levels, and widespread ocean acidification. These changes pose risks for a wide range of human and environmental systems, including freshwater resources, the coastal environment, ecosystems, agriculture, fisheries, human health, and national security [13].

Reducing general vehicle emissions is important because throughout the last 30 years, there have been a number of scientific studies indicating that particulate air pollution from ICE powered vehicles has an adverse effect on human health [14, 15, 16, 17, 18] especially in urban areas where emissions are more common [19-20]. Additionally, through the use of improved technology, it has been shown that existing emissions standards may need to be revised to account for the high level of fine particulate matter from vehicle emissions which is equally as detrimental to human health [21].

**Vehicle Architecture for Increasing Fuel Economy**

These three major drawbacks of ICE powered automobiles have sparked numerous new vehicle technologies such as Hybrid Electric Vehicles (HEVs), Plug-In Hybrid Electric Vehicles (PHEVs), Electric Vehicles (EVs), and Fuel Cell Vehicles (FCVs). Of these four alternate vehicle types, three are currently being sold to consumers and have sufficient infrastructure to sustain operation. The highest selling version of each of these vehicles is shown in figure 2 as well as the highest selling ICE only vehicle or conventional vehicle (CV). Each of the current production vehicle types has unique advantages and disadvantages when compared to CVs.

EVs allow freedom in choosing a power source and charging the vehicle via electricity. This vehicle type has the potential to eliminate the major drawbacks shown in figure 1 as long as the energy source is not fossil fuels [22]. Drawbacks to EVs that are preventing widespread adoption include the limited battery technology that significantly reduces the range of EVs (low power density in the battery), refueling/charging time, and cost [23,24].
PHEVs attempt to bridge the gap between EVs and CVs by allowing freedom to provide propulsion via electricity but also eliminate range anxiety by having a full ICE system. This vehicle type suffers from adoption issues and mass compounding design constraints of putting essentially two propulsion mechanisms in one vehicle [25, 26, 27].

Hybrid electric vehicles have the advantage that they can use existing fueling infrastructure, do not have to be plugged in, are technologically more mature, and have the highest range. The main disadvantage of HEVs is that they are slower and more complex. HEVs address the disadvantages of conventional vehicles in that they reduce the combustion required for energy through an increase in vehicle operation efficiency. The technology involved in improving HEV fuel economy also has the advantage in that it is a crucial step to obtain vehicle autonomy which has societal benefits [28]. Because of the advantages and technological maturity of HEVs, continued improvement of fuel economy through the closing of optimal energy management research gaps is a near term solution to produce a positive environmental and societal impact.

**Research Motivation**

In order to minimize the CV disadvantages presented in figure 1 while still adhering to consumer preference predicted until 2040, a maximization of FE for HEVs is the required solution. To improve HEV fuel economy, optimal control techniques can be employed using over nine different techniques that have been well documented in the literature [29,30]. But, there are research gaps preventing the technology from being implemented: sensor and signal technology and prediction scope and error impacts.

**Research Gap: Use of Sensor and Signal Technology for Fuel Economy Improvements**

Sensor and signal technologies can increase FE in two significant ways: (1) facilitation of more energy efficient driving behavior, also known as eco-driving, and (2) real world realization of the drive cycle prediction requirement of optimal energy management strategies. Sensor technologies that are currently available in modern commercial vehicles for safety and convenience but are not utilized to improve FE include: camera systems (CS), radar systems (VRS), and global positioning systems (GPS). Signals that are under development but currently nonexistent in modern commercial vehicles include: vehicle to vehicle communication signals (V2V), vehicle to infrastructure communication signals (V2I), and vehicle to the any/all connectible devices (V2X). Each sensor and signal technology will be discussed to show how it is currently being used and how it could be used to improve implementation of optimal energy management.

Research of vehicle camera systems’ (CS) ability to improve FE has received little attention. For eco-driving related FE improvements, CS can be used to identify system surroundings and choose the most FE vehicle drive cycle [31]. For optimal energy management FE improvements, CS can be used to achieve energy management strategies that require drive cycle prediction [32,33]. The addition of vehicle camera systems (CS) for improved driver safety has received considerable research attention [34, 35, 36, 37, 38, 39, 40] for applications such as tracking and identification of large road hazards [41], reliable interpretation of other vehicle types (truck, car, motorcycle, pedestrian etc.), reliable interpretation of traffic signs [35,42,43], and implementation of autonomous control [34, 43, 44, 45]. The difficulty of CS is that although they are a mature technology which can be implemented in the near term, they are limited by processing power, robustness of machine vision algorithms, and by visual obstructions such as available light, weather conditions, visibility, and resolution [39]. If visibility around the vehicle is obscured, the information provided by the camera system will not be accurate.

As with CS little research exists exploring the effect of vehicle radio detection and ranging (RaDAR) systems (VRS) on improved fuel economy for both eco-driving [46] and optimal energy management applications [47]. VRS have been in development for decades [48, 49, 50, 51, 52] but only recently have applications been developed to focus specifically on vehicle safety [53,54,55], and autonomous control implementation [52]. Compared to camera systems, vehicle RaDAR technology has the benefit of not being fouled by omission of light but it cannot extract finer details (e.g. the picture on a street sign). Because RaDAR is not fouled by bad weather or visual obstructions, it is robust for safety purposes. Additionally, the information obtained from RaDAR can be verified by light detection and ranging (LiDAR) which operates on the same principle but uses lasers and photonics instead of radio frequencies. In practice, LiDAR tends to be more accurate due to the precision of the lasers and beam diffusion at far distances while RaDAR has the advantage of lower cost since the technology is more developed and requires no moving parts [56]. LiDAR, RaDAR, and CS provide the most accurate and robust environmental sensing when employed together, stemming from a diverse range of data sources and the resulting cross verification of environmental signals [54, 57, 58, 59, 60].

As shown in figure 3, a combination of VRS and CS provides information about the close surroundings of the vehicle which provides a marginal vehicle operation prediction window for implementation of optimal energy management. The greatest FE gains have been shown with adaptive cruise control algorithms for such integrated sensor systems [47].

To move beyond interpretation of close vehicle surroundings and begin interpretation of drive cycle information, global navigation satellite system (GNSS) data is required. The current standard for GNSS data is from the United States’ global positioning system.
electric vehicles [36-66] energy management from the grid to power plug in hybrid and individual vehicle energy management and would allow for optimal energy management improvements from eco-driving. Communicating devices allows for the most extensive FE accurate and extensive signal communication between vehicle and all technology is known as vehicle to everything or V2X. Assuming vehicle to grid (V2G), vehicle to device (V2D), vehicle to pedestrian, discussion of all the remaining potential signals which include, One last signal technology subject for consideration is a brief drive cycle prediction, and eco-driving for maximal FE. Yields traffic information for detailed and accurate information becomes even more powerful when combined with V2V technology to statuses will be upon arrival along the drive cycle. V2I technology be achieved with foreknowledge of what each of the traffic light encountering over a full drive cycle; improved vehicle speed required technology in order to accurately predict the complexities encountered over a full drive cycle; improved vehicle speed prediction results in improved vehicle FE with optimal control [83].

The other critical signal technology for use with GNSS and V2V for accurate prediction of a full drive cycle is communication between vehicles and infrastructure (V2I). A simple yet powerful version of this technology is the communication between vehicles and traffic lights which has tremendous safety and FE benefits. V2I is also a critical component for the prediction of drive cycle details such as stop signs, construction events, and traffic lights [84, 85, 86]. For a basic drive cycle prediction, all that is required is a map, a beginning location, and an ending location [87]. A more precise drive cycle prediction can be achieved with foreknowledge of what each of the traffic light statuses will be upon arrival along the drive cycle. V2I technology becomes even more powerful when combined with V2V technology to yield traffic information for detailed and accurate information for full drive cycle prediction, and eco-driving for maximal FE.

One last signal technology subject for consideration is a brief discussion of all the remaining potential signals which include, vehicle to grid (V2G), vehicle to device (V2D), vehicle to pedestrian, and vehicle to cloud. When all vehicle signals are considered, the technology is known as vehicle to everything or V2X. Assuming accurate and extensive signal communication between vehicle and all communicating devices allows for the most extensive FE improvements from eco-driving [89-102] and energy management [103]. This technology also goes beyond individual vehicle energy management and would allow for optimal energy management from the grid to power plug in hybrid and electric vehicles [104] in addition to autonomous driving [105].

Sensor and signal technology is essential for improvements in fuel economy due to the dynamic nature of driving and road conditions and the integration of specific vehicle signals with eco-driving and HEV optimal energy management strategies needs more attention in research. As shown in table 1, there are sensing and signal technologies available in modern vehicles that could be used to improve current HEV fuel economy and there are many more useful sensor and signal technologies approaching commercial availability in the near future. Use of these signals to improve real world HEV fuel economy should be understood now so that the modern vehicle drawbacks shown in figure 1 can be reduced.

Research Gap: Optimal Energy Management Prediction Scope and Error Impacts

Optimal energy management strategies rely on prediction of future vehicle states; the longer the prediction window is, the higher the potential for improvement in fuel economy. But, until perfect prediction of the full vehicle drive cycle is achieved, a detailed understanding of the impact of prediction errors is required. The impact of prediction errors to FE from optimal energy management has received relatively little attention by researchers. In general, researchers have identified the need to expand the current research to include the effect of prediction errors [29-92] and the impact of prediction error has been speculated to be large [100].

It has been shown that current vehicle operation prediction techniques are not 100% accurate [101, 102]. Prediction algorithms have been developed that provide updates every 5 minutes and can predict

<table>
<thead>
<tr>
<th>Sensor or Signal Technology</th>
<th>Availability</th>
<th>Potential Mechanism for Fuel Economy Improvement with More Research</th>
</tr>
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<tbody>
<tr>
<td>Camera Systems (CS)</td>
<td>Currently in use</td>
<td>Localized eco-driving. Local prediction of drive cycle for optimal energy management.</td>
</tr>
<tr>
<td>Radar Systems (VRS)</td>
<td>Currently in use</td>
<td>Localized eco-driving. Local prediction of drive cycle for optimal energy management.</td>
</tr>
<tr>
<td>LiDAR Systems</td>
<td>Available but costly</td>
<td>Localized eco-driving. Local prediction of drive cycle for optimal energy management.</td>
</tr>
<tr>
<td>Global Positioning System (GPS)</td>
<td>Currently in widespread use</td>
<td>Route level eco-driving. Route level prediction of drive cycle for optimal energy management.</td>
</tr>
<tr>
<td>Improved Global Nav Satellite Sys. (GNSS)</td>
<td>2-5+ years before launch</td>
<td>Route level eco-driving. Route level prediction of drive cycle for optimal energy management.</td>
</tr>
<tr>
<td>Vehicle to Vehicle Comm. (V2V)</td>
<td>~10 years, government dependent</td>
<td>Full drive cycle eco-driving. Full prediction of drive cycle for optimal energy management.</td>
</tr>
<tr>
<td>Vehicle to Infrastructure Comm. (V2I)</td>
<td>5-10 years, government dependent</td>
<td>Full drive cycle eco-driving. Full prediction of drive cycle for optimal energy management.</td>
</tr>
<tr>
<td>Vehicle to Everything Comm. (V2X)</td>
<td>10+ years, government dependent</td>
<td>Full drive cycle eco-driving. Full prediction of drive cycle for optimal energy management.</td>
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</table>

Table 1. A comparison of various sensor and signal technologies that could be used to improve the fuel economy of hybrid electric vehicles and the mechanisms that could provide an improvement in fuel economy with more research (note the correlation with the information shown in figure 3).
traffic for up to 1 hour. One technique in the literature shows traffic speed and volume prediction accuracy above 85% for 5 minutes of prediction to 60 minutes of prediction [103]. Real travel time prediction has also been recently expanded from highway travel to urban travel with prediction relative mean errors as low as 10.8% [102]. Integration of these errors with HEV optimal energy management is not well addressed and the impact of these errors is not well understood.

One study that investigates the impacts of prediction errors on an optimal energy management strategy fuel economy improvements chose to analyze stochastic or random drive cycle energy prediction errors of up to 20% and an optimal energy management strategy of Adaptive-Equivalent Consumption Minimization Strategy (A-ECMS) [104,105]. These researchers found that FE performance was degraded when the energy management scheme was exposed to prediction errors but they could not find a correlation between the mean average percent error and FE performance [104]. This analysis is compared to other optimal energy management prediction error analyses in figure 4.

Another research group studied the effect of velocity profile prediction errors in a model predictive control (MPC) and an AECMS based optimal energy management scheme. In this study, real world driving data was used to predict the vehicle velocity data for alternate real world drive cycles. Their results shown that the drive cycles with error and the drive cycles with no error have equivalent FE gains [106]. In each case, the FE and final SOC value were different but, a net FE benefit was achieved in MPC and A-ECMS control strategies. Note that optimal energy management derivation algorithms such as A-ECMS incorporate random predictions and are expected to be robust against error.

In the analysis of co-operative adaptive cruise control (CACC) for diesel engine powered vehicles, one group of researchers analyzed imperfect predictions of vehicle speed [76]. When a following vehicle is using CACC and receives imperfect prediction data, a FE benefit is still achieved in vehicle following distances from 10m to 100m using a nonlinear autoregressive neural network to derive the optimal control. Additionally, when the drive cycle length is increased, a larger FE benefit is obtained for the considered disturbances.

Other researchers have also demonstrated a robustness from optimal energy management derived using Pontryagin’s minimization principle (PMP) when the drive cycle is subject to prediction error [107]. Prediction error was quantified as the root mean squared value of the difference in predicted velocity and actual velocity. These researchers were able to correlate prediction error and realizable FE improvement and showed an increase in FE for all PMP optimized control strategies relative to current vehicle controllers.

Our research group has analyzed the real world implementation of optimal energy management subject to prediction errors that may be encountered with the technology of today. In one control scenario, dynamic programming (DP) is used to derive the optimal control for a full drive cycle assuming the vehicle velocity is known for the drive cycle duration in one second increments. An advantage of dynamic programming is that it also provides a control decision matrix for every possible state and time. Using this control decision matrix, real world disturbances were analyzed which include an unpredicted traffic signal, unpredicted traffic, and an unpredicted route change [108].

In previous work, our research group has also analyzed the effect of prediction errors in two alternate control schemes: segment energy estimation errors, and hill elevation errors. Again, using the decision matrix results from DP, prediction errors were analyzed and compared to the accurate prediction case [109]. For all three controls strategies, it was found that advanced energy management strategies are sensitive to prediction errors, but real world FE improvement are possible even with prediction errors. Both of these analyses are compared in figure 4.

In summary, understanding of prediction error impacts could facilitate near term implementation of optimal energy management techniques. Existing studies on this subject have begun investigating the impact of random prediction errors, real world velocity errors, and real world drive cycle disturbances. Because of the variety in energy management strategies, vehicle architectures, and useful drive cycles there is a significant need for more research in this area.

![Figure 4. Results comparison of existing research that analyzes the impact of various prediction errors to various energy management schemes (Note: each study uses a unique drive cycle).](image-url)
Conclusions

ICE powered automobiles currently on the road account for 61% of U.S. petroleum consumption, 28% of GHG emissions, and 33% and 36% of CO and NOX emissions making them the leading contributor in each of these categories. HEVs provide a significant improvement in FE and have large customer adoption. Through HEV energy management techniques, their fuel economy can be increased by approximately 20% with the filling of the presented research gaps thus reducing U.S. dependence on foreign oil, reducing climate change from GHG emissions, and reducing detrimental human health emissions.

One research gap preventing fuel economy improvement techniques for HEVs from being implemented is the utilization of sensor and signal technology. Sensors such as camera systems and RadAR systems already exist in modern vehicles but remain unutilized for eco-driving and optimal energy management fuel economy improvements. Signal technology such as V2V, V2I, and V2X will be available in the near term but their gradual implementation impact on eco-driving and optimal energy management remains unknown. More research on the fidelity and accuracy of the drive cycle predictions achievable through various combinations of currently available and near term available sensor and signal technology is required to achieve HEV fuel economy improvements.

Another research gap preventing implementation of optimal energy management fuel economy improvements is the lack of research data on the impact of prediction errors. Initial research is this area has begun by investigating the impact of stochastic or random errors on stochastic derived optimal control strategies as well as the impact of velocity mis-predictions, energy mis-predictions, stoplight mispredictions, and traffic mis-predictions on globally optimal energy management strategies. Because there is a large variety of HEV architectures, drive cycles, optimal energy management strategies, and mis-predictions types, this research gap needs significant attention.

The impact of real world implementation of optimal energy management techniques has the potential to benefit political compliance, the environment, and human health. It has been well established that optimal energy management provides a large FE benefit but OEM production vehicles utilizing these techniques is not possible without closing the three research gaps presented here.

The future of FE relies on the optimization of HEV eco-driving and energy management. It has been well documented in the literature that FE improvements from 20-30% are possible in a world of autonomous vehicles and perfect drive cycle prediction but part of this FE improvement could be realized today and in the near term through investigation of sensor and signal technology predictions and prediction error impacts on optimal energy management. Quantification and understanding of prediction errors will drive the need for sensor and signal technology so that the well-established optimal energy management control techniques can be utilized in the next generation of consumer vehicles.

References

2. Exxon Mobil. The Outlook for Energy 2016. 2015.
15. Krzyżanowski M, Kuna-Dibbert B, Schneider J. Health Effects of Transport-related Air Pollution. WHO Regional Office Europe; 2005.


61. Stenborg E, Hammarstrand L. Using a single band GNSS receiver to improve relative positioning in autonomous cars 2016.


73. Li Z, Kumar BVKV, Bai F. A double decoding scheme to improve the per performance of V2V communications. IEEE Wirel Commun Netw Conf WCNC 2013:3838-43. doi:10.1109/WCNC.2013.6555187.


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Definitions/Abbreviations

A-ECMS - Adaptive Equivalent Consumption Minimization Strategy
CO - Carbon Monoxide
CS - Camera Systems
CV - Conventional Vehicle
DP - Dynamic Programming
ECMS - Equivalent Consumption Minimization Strategy
EV - Electric Vehicle
FE - Fuel Economy
GDP - Gross Domestic Product
GHG - Greenhouse Gas
GNSS - Global Navigation Satellite System
GPS - Global Positioning System
HEV - Hybrid Electric Vehicle
ICE - Internal Combustion Engine
LiDAR - Light Detection and Ranging
MPC - Model Predictive Control
N/A - Not Applicable
NN - Neural Network
NOx - Mono-Nitrogen Oxides
PHEV - Plug-In Hybrid Electric Vehicle
PMP - Pontryagin’s Minimization Principle
RaDAR - Radio Detection and Ranging
V2I - Vehicle to Infrastructure
V2V - Vehicle to Vehicle
V2X - Vehicle to Everything
VRS - Vehicle RaDAR Systems