1.0 Introduction

1.1 Personal Transportation and Climate Change

Road vehicles are a key part of the climate change challenge, representing both an important source of petroleum demand and greenhouse gas (GHG) emissions worldwide. In the United States, light-duty vehicles (LDVs, i.e., cars and light trucks) alone account for 43% of petroleum demand and 23% of GHG emissions, when fuel production is considered [MacKenzie, 2013]. The United States, Europe, China, and Japan consume over half of the world’s petroleum, making them particularly critical in efforts to reduce petroleum consumption and the associated emissions. The production and use of gasoline and distillate (diesel) fuel in these four regions alone account for 15% of the world’s energy-related carbon dioxide (CO₂) emissions [Energy Information Administration (EIA), 2013a]. Changes in our transportation system are necessary to mitigate climate change.

Changes to our transportation system—how much we travel, the vehicles we use, and the fuels that power them—offer the potential for substantial reductions in GHG emissions. This report is a synthesis of research conducted in the Sloan Automotive Laboratory at the Massachusetts Institute of Technology over the past five years, primarily under the direction of Professor John Heywood. It is the third report in a series that records the research findings of this group. The others are On the Road in 2020 [Weiss et al., 2000] and On the Road in 2035 [Bandivadeker et al., 2008].

This research addresses topics related to the evolution of vehicle technology and its deployment, the development of alternative fuels and energy sources, the impacts of driver behavior, and the implications of all of these factors on future GHG emissions in the United States, Europe, China, and Japan.

1.2 The Clock Is Ticking

This report is motivated by the simple observation that time is of the essence as we attempt to deal with the threat of climate change. Despite many warnings from the scientific community and the concern from some of our leaders, the levels of GHGs in the atmosphere continue to increase. In 2013, the average daily CO₂ level measured at Mauna Loa, Hawaii, topped 400 parts per million (ppm) for the first time [Scripps, 2013]. The annual average CO₂ concentration at Mauna Loa has increased every single year since record-keeping began (Figure 1.1). Whereas CO₂ concentration increased by less than 1 ppm per year during the 1960s, it has increased by more than 2 ppm annually since 2000. We must make increasingly substantive progress on reducing GHG emissions as we move forward from today if we are to avoid the anticipated damaging effects of climate change.
Strategies to mitigate climate change must recognize the cumulative nature of the buildup of GHG concentrations in the atmosphere. CO₂ and other GHGs, once released into the atmosphere, accumulate there and are only slowly removed. Moreover, the impacts that they cause are largely dependent upon their concentrations. This has two critical implications for GHG mitigation strategies:

1. To avoid an inexorable increase of GHG concentration levels, GHGs must not be added to the atmosphere any faster than they can be removed. This means that over the long term, emissions from fossil fuel carbon will need to be stabilized at levels substantially lower than today’s levels, and possibly close to zero.

2. If GHG concentrations are to be stabilized at tolerable levels, there is an upper limit to the total amount of carbon (and GHGs) that can be dumped into the atmosphere. Thus, we cannot wait indefinitely to make the aforementioned switch to a radically less carbon-intensive energy system.

Transitioning to new energy sources takes decades. As shown in Figure 1.2, coal, oil, and natural gas each took 50–75 years to reach their peak levels of use. An extrapolation of the trend in Figure 1.1 indicates that we are on track to exceed 450 ppm of CO₂—a threshold widely held to be necessary for avoiding the worst effects of climate change—within just 25 years. Even if we begin to transition earnestly to radically lower-carbon energy sources today, we will still continue to rely on fossil fuels for many years to come.

Figure 1.1  Annual average CO₂ concentration (ppm) at Mauna Loa Observatory, Hawaii, 1959–2012 [NOAA, 2013]
An effective strategy for mitigating GHG emissions must, therefore, have both near- and long-term components: a set of long-term solutions to get us to near-zero carbon emissions and near-term actions that can buy us enough time to develop and deploy the long-term solutions. While near-zero carbon energy sources will be needed in the long term, we simply do not have the luxury of waiting to act until these low-emitting alternative energy sources are developed. Reducing demand for energy-using services and increasing the energy efficiency of those services can provide relatively cost-effective reductions in energy demand and emissions, while also buying critical time for alternative energy sources to be developed and deployed. This is illustrated in Figures 1.3 and 1.4.

In Figure 1.3, immediate efforts at improving fuel consumption and conservation lead to reductions in GHG emissions in the near and medium terms. As the potential savings from fuel consumption begin to level out, the transformation toward low-carbon fuels begins to pick up speed and enables continued GHG reductions. Figure 1.4 shows how efforts focused solely on transforming the transportation energy supply lead to continued growth in emissions for several decades, before the alternative fuel technologies begin to grow rapidly. In the meantime, large quantities of GHG will have accumulated in the atmosphere and exceeded the available carbon budget.
Figure 1.3  GHG emissions pathways under four scenarios: business as usual, improve-only, improve and conserve, and improve-conserve-transform

Figure 1.4  GHG emissions pathways under four scenarios: business as usual, transform-only, improve and transform, and improve-conserve-transform
1.3 **Improve, Conserve, Transform**

The central premise of this report is that a comprehensive strategy for mitigating GHG emissions from our vehicles will include several interrelated sets of actions:

1. **Improving** the fuel economy of conventional, petroleum-powered vehicles through steady gains in powertrain efficiency, reductions in vehicle weight, and assigning a higher priority to lower fuel consumption than to other design goals.

2. **Conserving** energy through changes in individual behavior, such as reducing travel demand, shifting to less energy-intensive travel modes, and operating vehicles more efficiently.

3. **Transforming** the transportation system into one that is radically less carbon intensive, through significant gains in vehicle efficiency and/or a large-scale switch to carbon-neutral energy sources.

These broad strategies are informed by viewing the generation of GHG emissions through a Kaya identity or “ASIF” framework [Schipper, 2002]. This framework notes that the rate of GHG emissions can be calculated from:

\[
GHG = \frac{\text{Person Miles}}{\text{Vehicles Miles}} \cdot \frac{\text{Energy}}{\text{GHGs}}
\]

or

\[
GHGs = A \times S \times I \times F
\]

In Schipper’s ASIF formulation, \(A\) refers to activity level (person-miles of travel); \(S\) to the mode structure or mix (e.g., \(S = 0.65\) vehicle-miles / person-mile for cars in the United States); \(I\) to energy intensity or fuel consumption; and \(F\) to fuel carbon content. Viewing GHG emissions through this framework emphasizes the fact that improvements in any one of these factors contributes to proportional reductions in GHG emissions. However, it is important to consider that changes in one factor may lead to changes in other factors. For example, changing energy intensity is likely to change person miles of travel and vehicle miles per person-mile through the well-known rebound effect.

Proponents of the familiar “three-legged stool” approach have long asserted that vehicle fuel consumption, travel demand, and alternative fuels should be a part of a comprehensive GHG mitigation strategy. The authors of *Moving Cooler* [Cambridge Systematics, 2009] introduce a fourth category of options that relates to vehicle and system operations. Whereas *Moving Cooler* primarily addresses solutions relating to travel activity and vehicle and system operations, our report focuses primarily on vehicle technology, alternative fuels, and individual driving habits.
**Content of this Report**

This report addresses the range of propulsion system, vehicle technology, and fuel options available to help mitigate petroleum consumption and GHG emissions from automobiles in the United States and in other major regional markets. It also contains retrospective analyses of efficiency technology improvements in the United States, and examines historic adoption patterns of vehicle technologies. It studies the impacts of individual driving behavior on petroleum consumption. Finally, it presents a range of scenarios characterizing the ways that transportation systems could evolve in major global markets over the coming decades, and evaluates the cost effectiveness of various policy approaches for driving this evolution.

**Chapter 1** lays out the basic challenge, which is the urgent need to reduce the GHG emissions from light-duty (predominantly private) vehicles through reductions in petroleum consumption and the substitution of alternative lower-carbon-emitting fuels and other sources of energy. We have also introduced the three broad paths forward that are of comparable importance and urgency: improving the fuel consumption of mainstream-technology vehicles; conserving fuel and energy use through how and how much we drive; and exploring the eventual transformation from our current situation in which internal combustion engine vehicles and petroleum-based fuels dominate our in-use light-duty fleet to alternative travel approaches that use energy sources that have modest impacts on our environment and are ultimately more sustainable. We have outlined here the factors that together provide a structured framework for assessing our options. It is important to keep these broad themes in mind as we progress, topic by topic, through the 11 chapters of the report.

**Chapter 2** revisits past work by this research group and highlights some recent major reports from other groups in order to provide context for the present work and the motivation for the Improve-Conserve-Transform framework. The chapter outlines the steps that would be necessary to attain 80% reductions in GHG emissions by 2050. It concludes that aggressive efforts to conserve energy through individual behavior change, the rapid improvement of conventional vehicles, and the transition to radically less carbon-intensive alternatives will need to begin promptly.

**Chapter 3** presents an overview of the major propulsion systems options that are available to improve energy intensity and transform the transportation system away from its current reliance on petroleum. It provides an assessment of feasible rates of improvement and examines the ways that the potential improvements vary across different global markets.

**Chapter 4** examines the evolutionary changes in weight of U.S. cars over the past 35 years. It addresses the tension between steady improvements in weight-saving technologies and the steady introduction of new features and capabilities that have added weight to cars. It then applies these insights to assess the potential for weight reduction in the future.

**Chapter 5** addresses the trade-offs between vehicle fuel consumption, acceleration performance, and weight. It explores the implications of changes in these vehicle attributes for efforts to improve fuel consumption. The chapter provides estimates of the fuel consumption impacts of changes in acceleration and weight, and reviews the Emphasis on Reducing Fuel Consumption (ERFC), a parameter that characterizes the degree to which efficiency improvements
have been realized as reductions in fuel consumption. It examines ERFC over the past 35 years and quantifies the roles of other design changes—most notably gains in acceleration performance—that have acted as “sinks” for technology improvements. Given these findings, the chapter closes with an assessment of potential future levels of emphasis on reducing fuel consumption.

Chapter 6 introduces a framework for evaluating the prospective transformation to alternative fuels as the primary sources of energy, highlighting the many challenges to adopting these alternative fuels, including cost, environmental impact, GHG emissions, and compatibility with vehicles and infrastructure.

Chapter 7 presents key results relating to the adoption of new technologies, with implications both for the improvement of conventional technologies and the transformation to alternative powertrain systems. The chapter first discusses the adoption of powertrain, safety, and comfort and convenience features, characterizing their saturation levels and speed of adoption. Next, it presents a model of the adoption of a much more complex technology: hybrid electric drive as represented by the Toyota Prius. Finally, it discusses how the adoption and deployment of new technologies will propagate into and through the on-the-road vehicle fleet through fleet turnover.

Chapter 8 examines several opportunities for conservation. It briefly summarizes research estimating the potential for GHG savings through reductions in travel demand as well as through improvements in transportation system operations. It then presents new work characterizing the aggressiveness of driving, and the implications of aggressiveness for in-use fuel consumption. Finally, it presents the results of a large-scale, plug-in hybrid electric vehicle (PHEV) demonstration, highlighting the significant variability in petroleum savings across different drivers, characterizing factors related to battery charging decisions, and examining the potential petroleum savings from changing charging decisions or from changing battery sizes.

Chapter 9 summarizes several scenarios exploring the potential energy consumption and GHG emissions trajectories from personal transportation in major regions of the world. Each scenario is based on assumptions regarding the evolving context for vehicle deployment and use (e.g., growth in new vehicles sales, mileage driven), the rate of improvement in the various efficiency-improving technologies and their rate of deployment, the development of alternative fuel supplies, and the GHG emissions intensities of these new fuel supplies. These scenarios allow us to assess the uncertainties in the projected impacts, the overall rate of progress in reducing these impacts, and the factors that have the largest effects on outcomes.

Chapter 10 discusses the role of a comprehensive policy approach in driving improvement, conservation, and transformation. It also presents results comparing the cost effectiveness of carbon and fuel taxes to fuel economy standards and renewable fuel standards in achieving emissions reductions.

Chapter 11 pulls together the findings in each of the preceding chapters and concludes with a discussion of where we are, where we are headed, and where we need to go.
References


EIA (2013b). Total Energy, Figure 5. U.S. Energy Information Administration. Available online: http://www.eia.gov/totalenergy/data/annual/perspectives.cfm


