Optimal fleet conversion policy from a life cycle perspective

Hyung Chul Kim, Marc H. Ross, Gregory A. Keoleian *

Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan, 430 E. University, Ann Arbor, MI 48109-1115, USA

Abstract

Vehicles typically deteriorate with accumulating mileage and emit more tailpipe air pollutants per mile. Although incentive programs for scrapping old, high-emitting vehicles have been implemented to reduce urban air pollutants and greenhouse gases, these policies may create additional sales of new vehicles as well. From a life cycle perspective, the emissions from both the additional vehicle production and scrapping need to be addressed when evaluating the benefits of scrapping older vehicles. This study explores an optimal fleet conversion policy based on mid-sized internal combustion engine vehicles in the US, defined as one that minimizes total life cycle emissions from the entire fleet of new and used vehicles. To describe vehicles’ lifetime emission profiles as functions of accumulated mileage, a series of life cycle inventories characterizing environmental performance for vehicle production, use, and retirement was developed for each model year between 1981 and 2020. A simulation program is developed to investigate ideal and practical fleet conversion policies separately for three regulated pollutants (CO, NMHC, and NO\textsubscript{x}) and for CO\textsubscript{2}. According to the simulation results, accelerated scrapping policies are generally recommended to reduce regulated emissions, but they may increase greenhouse gases. Multi-objective analysis based on economic valuation methods was used to investigate trade-offs among emissions of different pollutants for optimal fleet conversion policies.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Vehicle scrappage; High-emitter; Life cycle assessment; Air pollutant emissions; Greenhouse gas

1. Introduction

Currently, over 120 million passenger cars are in use in the US. Of these, more than 17 millions are 15 years or older (Davis, 2001). Since the 1970s, the expected lifetime of US vehicles has
increased considerably. One study predicts that the median lifetime of a 1990-model car will be 16.1 years, compared with 11.5 years for a 1970 model (Davis, 2001). With increasing age and mileage, vehicles typically deteriorate and emit more CO, HC, and NO\textsubscript{x} pollutants per mile driven.

Vehicle deterioration is categorized in two different ways: the degradation of normal-emitters and the increasing number of high-emitters. Normal-emitters are regularly maintained and properly driven vehicles that emit less than regulatory standards when tested according to the federal test procedure (FTP). The degradation of normal-emitters is a gradual process associated with the mileage and model year of a vehicle. Austin and Ross described the normal-emitter’s FTP tailpipe emissions (CO, HC, and NO\textsubscript{x}) as proportional to mileage based on the EPA’s long-term in-use emission survey data (Austin and Ross, 2001). According to this research, emissions of new cars and degradation rates depend on the model year and odometer readings. On the other hand, high-emitters, often associated with malfunctions of emission control systems, emit pollutants at considerably higher rates than permitted by regulatory standards. High-emitters result from the failure of components, improper repair, and other occasional abuses of drivers. The number of high-emitters also depends on the model year and mileage of a vehicle.

The efforts to reduce the ‘in-use’ emissions from old or high-emitting vehicles include scrappage programs, which recruit and retire old vehicles by compensating their owners based on the estimated amount of emissions saved by their retirements. Several studies have analyzed the trade-offs between the saved HC and NO\textsubscript{x} emissions versus the cost of scrapping old cars (US Congress, 1992; Alberini et al., 1995; Hahn, 1995). In these studies, the optimal scrap values and participation rates of the scrappage programs were derived using a range of prices offered for the scrapped car. However, these studies failed to consider other sources of emissions: dismantling old vehicles and producing new vehicles to replace them.

A recent study by the European Conference of Ministers of Transport (1999) concluded that scrappage schemes have both positive and negative impacts on the environment. The positive impacts include the reductions of atmospheric emissions when new vehicles replace old vehicles, while negative impacts arise from the increased emissions and resource consumption from the additional vehicle scrapping and production process. In fact, the early scrapping of old or worn-out vehicles is known to increase demand for new vehicles (Bohn, 1992). Thus, previous analyses of the effectiveness of scrappage programs may have been exaggerated, since the negative impacts of vehicle production and disposal were ignored.

The environmental impacts from the complete vehicle life cycle can be measured using life cycle assessment (LCA) methodology. This provides a holistic environmental profile for a product life cycle that includes materials production, manufacturing, use, maintenance, and end-of-life stages. The first comprehensive LCA study of a total vehicle was undertaken by the US Automotive Materials Partnership (USAMP). In this project, a generic vehicle was defined as a synthesis of three comparable 1995 mid-sized, five-passenger vehicles: the Dodge Intrepid, the Chevrolet Lumina, and the Ford Taurus. Life cycle inventory models were developed for each material and component of the generic vehicle primarily based on North American manufacturing norms and vehicle operation (Keoleian et al., 1998; Sullivan et al., 1998).

This study seeks to optimize a program for scrappage of older cars, referred to as a ‘fleet conversion policy’, based on the life cycle inventories of mid-sized internal combustion engine vehicles in the US. The optimal policy will minimize total emissions of each regulated pollutant...
(CO, NMHC, and NOx) as well as greenhouse gas emissions (CO2) from a fleet of vehicles, while maintaining the total mileage driven by the fleet. The results of this simulation will provide the threshold ages for vehicle scrapping and the number of new vehicles to replace the scrapped vehicles that minimize fleet emissions of an individual pollutant. In addition, multi-objective analysis of select air emissions is conducted using economic valuation methods to assess the relative importance of different pollutants.

This analysis assumes that only the age (and thus the accumulated mileage) of the vehicle, and not the condition of its emissions control system, affects its owners’ decision to scrap the vehicle. Some programs have used inspections to identify vehicles most appropriate for scrappage. That option is not evaluated here. Therefore, the policy recommendations in this study do not require the identification of normal- versus high-emitters.

This study constructs a model based on the life cycle inventory of a generic vehicle. Unlike the previous studies on scrappage programs that focused on the use stage of vehicles, the scope of this study accounts for the entire life cycle of vehicles: materials production; manufacturing; use; maintenance; and end-of-life.

2. Fleet characterization

The first step in determining optimal fleet conversion is to characterize the status quo of the fleet. A vehicle fleet is characterized by its age distribution and typical mileage accumulation patterns for vehicles within each age category. Figs. 1 and 2 show the distributions of the survival fraction (the fraction of vehicles of each age expected to survive to the next year) and annual vehicle miles traveled (VMT) by age for the passenger car fleet in the US. This study uses the fleet characterization data prepared for the MOBILE6 emission model as the primary source (Environmental Protection Agency, 1998). MOBILE6 is a computer model developed to simulate emission factors. The expected survival curve for MOBILE6 shown in Fig. 1 is based on 1996...
vehicle registrations (Environmental Protection Agency, 1999a). Since this curve is the snapshot of 1996 fleet, however, it represents the features of 1996 vehicle population rather than the survival profile of a generic vehicle. In fact, the populations of some mid-1980s models in 1996 were actually larger than some early 1990s models because the recession of the early 1990s dampened sales of new vehicles of those model years, and the usually high survival rate of the first 10 years in the curve may reflect this anomaly.

Due to the large number of variables associated with vehicle scrapping rates, such as local climate and road conditions, estimating a single nationwide survival curve may pose significant uncertainties. This study uses two additional survival curves to examine the sensitivity of the analysis: the survival rates of passenger cars used in the EMFAC2000 emission model developed by the California Environmental Protection Agency (2000); and the fitted automobile survival rates for model year 1990, estimated by the Oak Ridge National Laboratory (ORNL). The EMFAC2000 survival curve is derived from registration rates in consecutive calendar years for vehicles of specific models. The survival curve used in the EMFAC2000 reflects, however, the vehicle scrapping characteristics for the State of California, which are likely to differ from the national average due to climate and economic differences. The ORNL survival rates are calculated by fitting a scrappage model to actual registration data for vehicles of given model years during successive calendar years (Davis, 2001). As seen in Fig. 1, for older cars (14–30 years old), the survival rate estimates in the EMFAC2000 and ORNL curves are higher than those in the MOBILE6 curve, which implies that a larger fraction of the fleet consists of older vehicles. On the other hand, the MOBILE6 survival rates for younger cars (1–12 years old) are roughly equal to or slightly higher than other estimates.

The annual VMT of a surviving car in Fig. 2 is a curve-fit result based on the 1995 Nationwide Personal Transportation Survey (NPTS). This curve shows the annual VMT profile of a surviving car as a function of vehicle age. Combining these data with the survival rates for vehicles of different ages from MOBILE6, shown previously in Fig. 1, yields the expected annual VMT of a car initially manufactured during a given model year over its lifetime.
3. Sources of emissions

The emissions included in this simulation include carbon monoxide (CO), non-methane hydrocarbons (NMHC), oxides of nitrogen (NO\textsubscript{x}), and carbon dioxide (CO\textsubscript{2}). Life cycle energy consumption correlates very closely with life cycle CO\textsubscript{2} emissions, so that the simulations focusing on these two objectives are virtually equivalent. For this study, CO, NMHC, and NO\textsubscript{x} are characterized as regulated pollutants (or emissions) while CO\textsubscript{2} is categorized as a greenhouse gas. Since this study analyzes gasoline engine vehicles, other regulated pollutants like particulate matter (PM) and formaldehyde (HCHO) are not taken into account. In addition, other greenhouse gases such as methane are not considered, due to the limited availability of data on their emissions and the dominant role of CO\textsubscript{2} in total greenhouse gas emissions occurring during a vehicle's life cycle.

The sources of these emissions encompass a complete vehicle life cycle: material production, manufacturing and assembly, use, maintenance and repair, and end-of-life phase. Upstream energy production activities, such as fuel processing and distributions, create significant emissions as well. For this study, the emissions are based on the life cycle inventory (LCI) analysis of a generic vehicle conducted by USAMP. The primary goal of the USAMP project was to benchmark the environmental performance of a current mid-sized generic vehicle as well as future vehicle technologies. The analysis measured the environmental burdens from the life cycle of 1995 mid-sized vehicle, including raw material use, emission and waste outflows, and energy use (Keoleian et al., 1998; Sullivan et al., 1998). The USAMP LCI accounts for vehicle life cycle emissions and total fuel cycle-related emissions.

Vehicles of each age making up the fleet specified are characterized by different environmental impacts. While older vehicles emit more pollutants and consume more energy per mile driven, older vehicles are likely to be driven less than new vehicles due to their lower reliability, inferior performance, and other driver’s preferences. Thus, it is necessary to describe the environmental burden of a single vehicle as functions of its model year and accumulated mileage. The data for model years between 1981 and 2020 are derived in separate research using a dynamic LCI to estimate and forecast the life cycle inventories based on model year and vehicle mileage (Kim and Keoleian, 2001). The dynamic LCI uses the USAMP analysis of a 1995 mid-sized vehicle as a basis to derive the inventories as functions of age (or mileage) and model years. Actual trends through the mid-90s are used to help forecast changes through 2020, but other analyses in the literature are also used in the forecast. The methodologies and major assumptions for the dynamic LCI include:

- Materials composition of vehicles, recycled contents of vehicle materials, and energy intensities determine a vehicle’s contribution to the dynamic LCI for the materials production phase. For example, the major assumptions between 1981 and 2020 for aluminum include: the total weight of aluminum in a mid-sized generic vehicle will increase 71%; the recycled content of the rolled and extruded aluminum will increase from 11% to 48%; energy intensity in aluminum production will decrease 24% (Kim and Keoleian, 2001).

- The environmental burdens for the manufacturing and assembly phases are proportional to total vehicle weight. The total weight of a mid-sized generic vehicle is assumed to decrease 17% between 1995 and 2020 while decreasing 0.6% between 1981 and 1995 (Binder, 2000; Office for the Study of Automotive Transportation, 2000; Weiss et al., 2000).
CO, NMHC, and NO\textsubscript{x} emissions increase with vehicle mileage in two different modes: the continuous degradation of normal-emitters, and the stochastically increasing number of high-emitters. The EPA’s long-term federal test procedure (FTP) surveys are used to model the test-cycle emissions from normal-emitters as a function of accumulated vehicle mileage. The probability of a vehicle becoming a high-emitter is also modeled as a function of accumulated mileage, while the resulting increase in emissions is based on an analysis of emissions of vehicles tested on the IM240 cycle in Wisconsin between 1996 and 1998 (Ross and Wenzel, 1998). (The IM240 test is comparable to the third stage of the FTP.) Off-cycle and evaporative emissions were separately estimated to account for emissions that occur when vehicles are operated under conditions not represented in the FTP type emissions, and hydrocarbon emissions resulting from evaporation from vehicles’ fuel tanks and fuel delivery systems (Austin and Ross, 2001). Therefore, the emission factor \( E \) is determined by the sum of contributions from FTP normal-emitter \( E_N \), plus incremental emissions from three sources: FTP high-emitter \( E_H \), non-FTP or off-cycle driving \( E_{off} \), and non-FTP evaporation \( E_{evap} \).

Tier 2 emission standards for cars will phase in between 2004 and 2007, resulting in NMOG/CO/NO\textsubscript{x} fleet averages of 0.075/3.4/0.05 (g/mile) at 50,000 miles, and 0.09/4.2/0.07 (g/mile) at the full useful life (defined as 120,000 miles) (Environmental Protection Agency, 1999b). Vehicle manufacturers’ compliance margins for the tier 2 standards are assumed to be 70% at 50,000 miles and 60% at 120,000 miles for normal-emitters.\(^1\) For example, the FTP-type NO\textsubscript{x} emissions of a model year 2007 mid-sized vehicle are estimated to be 0.035 g/mile at 50,000 mile, increasing to 0.042 g/mile at 120,000 miles. It is assumed that the emission standards at 2020 will be 50\% of tier 2 and the compliance margins will be the same as those for tier 2. On the other hand, high-emitter contributions \( E_H \) to the emission factors \( E \) for model year 2007 through 2020 will equal 25\% of the tier 2 emission standards at 50,000 miles and increase in proportion to mileage (Kim and Keoleian, 2001). For example, the high-emitter contribution of NO\textsubscript{x} for model year 2007 will be 0.0125 g/mile at 50,000 mile and 0.03 g/mile at 120,000 miles.

EPA’s sales-weighted fuel economies represent nominal laboratory fuel economies of vehicle manufactured during model years between 1981 and 2000 (Environmental Protection Agency, 2000). These fuel economies are obtained by combining laboratory measures for both city and highway driving. The reference case forecasts of Annual Energy Outlook 2001 report are used to predict the nominal fuel economy of an average new car between 2000 and 2020 (Energy Information Administration, 2001). Although these nominal fuel economies are used for the Corporate Automotive Fuel Economy (CAFE) regulations, they are significantly higher than real-world estimates. To estimate the real-world fuel economies of mid-sized vehicles, the nominal fuel economies are multiplied by the conversion factor 0.806.

The environmental burdens from vehicle maintenance and repair are proportional to vehicle mileage since only scheduled and preventive services are taken into account.

The environmental burdens from the end-of-life phase, which include transportation of the used car, dismantling, shredding and disposal of the shredder residue, are proportional to total vehicle weight.

\(^{1}\) This information came from a personal interview with K. Cullen.
This study considers only gasoline-fueled internal combustion engine vehicles as future options due to the lack of LCI data for alternative-fuel vehicles. Upstream emissions associated with fuel production are also taken into account throughout the vehicle life cycle. Emissions occurring during feedstock extraction, fuel refining, storage, and distribution are based on the USAMP LCI analysis of a generic vehicle (Keoleian et al., 1998; Sullivan et al., 1998).

Fig. 3 shows the dynamic LCI emission profiles during the vehicle use phase, including maintenance and repair. CO\textsubscript{2} emissions, which depend on fuel consumption, remains constant with vehicle mileage for each model year because fuel economies are not likely to decrease with proper maintenance (Kim and Keoleian, 2001). The profiles of regulated emissions (CO, NMHC,
and NO\textsubscript{x}), on the other hand, vary with vehicles’ accumulated mileage. As can be seen in the figure, regulated emissions from 1980s model year vehicles increase sharply with vehicle mileage, mainly due to the low durability of catalysts and computer engine controls. The improved technology and stricter regulations have remarkably enhanced the durability as well as initial performance of emission control systems for 1990s model years (Austin and Ross, 2001). Moreover, the emission profiles for model year beyond 2000 show that tier 2 and further regulatory programs are assumed to further reduce emissions from both new and old vehicles.

According to the USAMP study, for the 1995 generic vehicle with a lifetime of 120,000 miles, emissions from the materials production and vehicle manufacturing phases account for 11.8% of life cycle emissions for CO\textsubscript{2}; 3.3% for CO; 8.1% for NMHC; and 8.4% for NO\textsubscript{x}. Fig. 4 shows the projected dynamic LCIs for the vehicle production phase including materials production, parts manufacturing, and vehicle assembly between model year 2000 and 2020. Depending on the specific pollutant, reductions of 28% to 35% are expected between model years 2000 and 2020, mainly due to the improvements in materials recycling and manufacturing energy efficiency. In addition, the end-of-life environmental burdens, which account for negligible life cycle emissions (<0.3%), are expected to decrease about 20% between model years 2000 and 2020 (Kim and Keoleian, 2001).

4. Fleet optimization modeling

4.1. Baseline fleet

To determine the optimal fleet conversion policy, it is important to develop a reasonable approximation of fleet conversion behavior in the real world. Fig. 5 depicts the simplified car population and VMT distribution during calendar year 2000, based on the MOBILE6 fleet characterization. This simplified baseline fleet characterization involves the following assumptions:
For simulation purposes, it is assumed that 100 new vehicles have been produced each year between 1981 and 2000.

All surviving vehicles are retired after 20 years of physical life.

These distributions will be repeated every year without interruption.
During the 20 years of physical life, vehicles can be retired from service due to crashes or mechanical failures. Let \( C(j) \) denote the vehicle population of age \( j \); then these natural retirements are characterized by an average failure rate or hazard rate at year \( j \), \( h(j) \). This rate is measured by:

\[
h(j) = \frac{C(j) - C(j+1)}{C(j)}
\]

Fig. 6 depicts the average hazard rate and the resulting pattern of vehicle retirements based on the MOBILE6 fleet characterization. This figure shows that MOBILE6 models the age distribution of the automobile population based on the combination of Weibull (between 1 and 12 years) and exponential distributions (beyond 13 years) (Environmental Protection Agency, 1999a).

4.2. Fleet optimization scheme

As with most scrappage models, the rationale behind the fleet optimization model is replacing ‘dirty’ old vehicles with ‘clean’ new vehicles. Fig. 7 describes the fleet optimization scheme, which determines the rate at which older vehicles should be retired and replaced with new models in order to minimize life cycle emissions from the entire fleet. As shown in Fig. 3, the life cycle emission of a vehicle increases with vehicle age (mileage), while decreasing with model year. Thus, the mileage inside the circle is driven with higher life cycle emissions compared with the mileage of first-year vehicles. The optimum fleet conversion seeks to reduce emissions by replacing high-polluting mileage with the same amount of clean mileage, while taking into account the emissions generated by vehicle production and end-of-life activities (transporting, dismantling, shredding, etc.).

4.3. Mathematical modeling

As already discussed, total emissions from the hypothetical fleet described in the previous section include those occurring during the entire vehicle life cycle. In order to simplify the
modeling equations, the vehicle life cycle will be organized into three phases: production, use, and end-of-life. The production phase accounts for the materials production as well as vehicle manufacturing phase, while the use phase includes maintenance as well as vehicle operation. The emissions from these phases are modeled as functions of calendar year (simulation year) \( i \) and/or vehicle age \( j \).

Emissions during vehicle production for calendar year \( i \), \( F_P(i) \), are determined by the population of age 1 vehicles during calendar year \( i \), \( C(i, 1) \), and production emissions per single vehicle, \( E_P(i) \).

\[
F_P(i) = C(i, 1) \cdot E_P(i)
\]  

(2)

The use phase fleet emission at year \( i \), \( F_U(i) \), is represented as the sum of use-related emissions from the vehicles of age 1 through \( L \), the maximum physical life (assumed to be 20 years). Let \( C(i, j) \) denote the population of vehicles of age \( j \) during calendar year \( i \), \( V(j) \) the mileage during the \( j \)th year of vehicle life, and \( E_U(i, j) \) the use emissions from the model year \( (i - j) \) vehicle during calendar year \( i \). Then total use emissions from the fleet in calendar year \( i \) is given by:

\[
F_U(i) = \sum_{j=1}^{L} C(i, j) \cdot V(j) \cdot E_U(i, j)
\]

(3)

The end-of-life contribution to emissions in calendar year \( i \), \( F_E(i) \), is the sum of two components—the emissions from the retirements caused by accidents or failures, plus the emissions from the forced retirements based on a scrappage program. To account for the rate of accidents or failures, the average hazard rate function, \( h(j) \), is incorporated into the equation.

\[
F_E(i) = \sum_{j=1}^{L} C(i - 1, j) \cdot h(j) \cdot E_E(i - 1, j) \\
+ \sum_{j=1}^{L} [C(i - 1, j) \cdot (1 - h(j)) - C(i, j + 1)] \cdot E_E(i - 1, j)
\]

(4)
The model problem is defined such that a decision maker with the baseline fleet distribution, \( C(i-1, j) \), at the end of year \((i-1)\) seeks the number of vehicle retirements and new vehicle replacements that will produce an optimal fleet age distribution at year \(i\), \( C^*(i, j) \). The optimal distribution is defined as one that will minimize total fleet emissions through year \(i\) while keeping total fleet VMT unchanged. Then, the fleet optimization model can be developed:

\[
\text{Minimize } F(i) = F_P(i) + F_U(i) + F_E(i) \\
\text{Subject to } h(j) = 1 \text{ for } j = L \\
C(i, j) = 0 \text{ for } j > L \\
\sum_{j=1}^{L} C(i-1, j) \cdot V(j) \leq \sum_{j=1}^{L} C(i, j) \cdot V(j) \\
\text{If } C(i, k) < C(i-1, k), \text{ then } \sum_{j=k+1}^{L} C(i, j) = 0 \text{ for all } k = 2, \ldots, L-1
\]

The first and second constraints force the retirement of \( L+1 \) year old vehicles after the maximum physical life \( L \), while the third constraint preserves the total fleet VMT unchanged when new vehicles replace retired vehicles. The last constraint will simplify the optimum solution by assuring that vehicles are first retired from the oldest age. In other words, \( k \)-year old vehicles can be retired only if the remaining \((k+1)\)-year old vehicles have first been completely retired.

Once the optimum fleet distribution is determined for year \(i\), then the optimum distribution for the year \(i+1\), \( C^*(i+1, j) \), can be obtained using the \( C^*(i, j) \) as the baseline fleet and repeating the same simulation. In this way, a longer-term fleet conversion policy can be constructed if the required data—life cycle emissions profiles over an extended period of vehicle model years—are available.

5. Results

The mathematical problem developed in the previous section has been solved using a computer program in C language. To determine the optimum fleet conversion policy, simulations that separately minimize each of CO, NMHC, NO\(_x\), CO\(_2\) emissions, and energy consumption have been conducted for calendar years between 2000 and 2020, using the maximum physical life \((L)\) of 20 years. The result for the energy consumption criterion has been exactly equivalent to that of CO\(_2\) emissions throughout the simulations of this study. Optimum fleet distributions, which are the result of simulations, are illustrated as age profiles of vehicles in service. The baseline fleet is characterized by the addition of 100 new cars each year without an accelerated scrapping program.

5.1. Ideal fleet conversion

The first simulations investigate the ideal fleet conversion during 2001, separately for each emission. Since these simulations do not limit the annual production capacity of the US, the outcomes of these model runs are likely to be purely mathematical solutions. Fig. 8 compares the
ideal fleet shapes and the emission savings from these fleet changes for the different categories of emissions.

The ideal fleet distribution in 2001 for CO₂ is identical to the shape for 2000—the baseline fleet distribution. This result implies that accelerated vehicle retirements will actually increase overall life cycle CO₂ emissions and energy consumption, since scrapping old vehicles will result in extra vehicle production to meet the total VMT constraint, and thus a net increase in energy use. In other words, the growth rate of new car fuel economy—the positive force for scrapping in the case of CO₂ emissions—is not large enough to justify scrapping old vehicles. On the other hand, the ideal fleet shapes for 2001 for the regulated pollutants (CO, NMHC, and NOₓ) show extensive elimination of old vehicles and sharp increases in the number of new vehicles. The most substantial change in the fleet age profile is required, and the largest emissions reduction is expected, to minimize CO emissions—scrapping vehicles older than 9 years and producing 379 new vehicles to replace their VMT. This result is due, in part, to the relatively small fraction of production CO emissions in the life cycle emissions profile of a vehicle, compared with NOₓ and NMHC.

5.2. Long-term fleet conversion

This simulation investigates realistic long-term policy options by allowing annual production up to 120 vehicles, a 20% increase from the assumed steady-state production capacity. This can be implemented by adding a constraint to the model:
In fact, new car sales have been fluctuating between eight and twelve million since 1970, and the maximum year-to-year fluctuation has been within ±20% (Binder, 2000). Fig. 9 shows the optimal fleet conversion policies separately for CO, NMHC, and NO\textsubscript{x} emissions between 2000 and 2020. These distributions are determined by repeating the model runs 20 times, using each previous year’s optimum as the baseline fleet. This analysis does not include CO\textsubscript{2} (energy) because, as shown in the previous section, any growth of vehicle production or scrapping will result in an increase in fleet CO\textsubscript{2} emissions (and energy use). Although different, each optimal conversion path requires a period of extensive production and scrapping, followed by a normal production and retirement period. For example, by producing 120 vehicles and eliminating high-emitting old vehicles for 3 years between 2000 and 2003, the NMHC emission will be minimized. The disrupted original fleet distribution will be recovered through normal production and retirement until the remaining ‘overproduced’ vehicles of model years 2000–2003 are retired after 20 years of physical life.

5.3. Emissions reductions

Emission reductions are calculated by comparing the emissions that will cumulate without policies, \(E_N(i)\), with emissions occurring under the optimal long-term policies discussed in the previous section, while allowing maximum vehicle production of 120 per year, \(E_O(i)\).

\[
\text{Relative reduction } (i) = \frac{E_N(i) - E_O(i)}{E_N(i)} \times 100(\%)
\]
Fig. 10 represents the emissions reductions that can be achieved through these long-term optimum fleet conversions. While the amounts of cumulative emission savings are greatest at 2020, the maximum relative reductions are found between years 2005 and 2015, with 5–9% reductions depending on the pollutants. Actual reductions could be larger than these estimates if emissions could be accurately measured and high-emitters properly identified in a real-world scrappage program. Moreover, this study does not account for the high-emitters older than 20 years, which may contribute significantly to real-world fleet emissions. The optimal fleet conversion policies will be the most effective and apparent within the initial 15-year period. These results suggest scrappage programs are temporary policies, whose initial effectiveness stems from the initial existence of significant numbers of high-emitters of the earliest model years represented in the fleet when a program is implemented.

![Graphs showing emission reductions over years for CO, NMHC, and NOx.](image)

**Fig. 10.** Emission reductions by the long-term optimal fleet conversion policy allowing 120 production.
5.4. Multi-objective analysis

This simulation attempts to investigate the fleet distribution that simultaneously optimizes multiple emission categories. This study uses a positive combination technique, one of the most commonly used practical techniques, for this multi-objective simulation. In a positive combination technique, the positive weight for each objective is determined based on priorities; a single objective function is defined by combining the weighted objectives; and the single objective function is then optimized (Murty, 1983).

One way to compare the priorities among emissions is to estimate the economic values of the emissions. Economic values for several pollutants have been estimated using a variety of methods including market valuation, estimated damage costs, and control cost estimates (Wang and Santini, 1994; Small and Kazimi, 1995). The resulting values vary by orders of magnitude among individual pollutants. This study focuses on a high and a low cost scenario for the regulated pollutants (CO, NO\textsubscript{x}, and NMHC), based on their estimated damage costs. On the other hand, the economic value of CO\textsubscript{2} is often measured by its marginal abatement cost (since little is known about damages resulting from potential climate changes), and typically increases with the size of the reduction. It also varies widely among countries depending on energy prices, energy supply structures, and the potential for renewable energy sources (Richels and Sturm, 1996; Criqui et al., 1999).

To investigate the optimal fleet distribution considering emissions of greenhouse gases and regulated pollutants simultaneously, simulations with a single objective—the total economic cost of combined emissions—has been conducted for calendar year 2001 for purposes of demonstration. An economic function \( U \) is defined using a weighting factor \( W \), economic cost or value per unit mass, for each pollutant:

\[
U = W_{CO} \cdot F_{CO} + W_{NMHC} \cdot F_{NMHC} + W_{NO_x} \cdot F_{NO_x} + W_{CO2} \cdot F_{CO2}
\]  

Then the model optimizes the total economic cost of emissions given by this function. Although some uncertainties are inevitable due to the significant variations in the estimated values of emissions, the main features of the simulation include a trade-off between the objectives of reducing greenhouse gases (CO\textsubscript{2}) and regulated pollutants (CO, NMHC, NO\textsubscript{x}). Fig. 11 highlights this trade-off using high and low damage cost estimates for regulated pollutants taken for different cities using the damage cost method (Environmental Protection Agency, 1992).

Many limitations exist with the applications of specific damage estimates to this study. For example, mobile (use phase vehicle tailpipe) and stationary source (vehicle production processes) emissions of the same pollutant are likely to have different impacts because of differences in pollutant dispersion and the size of human populations exposed. The y-axis in Fig. 11 represents optimum new production corresponding to the ideal fleet conversion for 2001 without a production limit, while the x-axis represents increasing CO\textsubscript{2} economic values. The principal result is that low values for reducing CO\textsubscript{2} emissions tend to support policies of accelerated-scrapping of older vehicles and extra-production of new vehicles to replace them. In other words, a relatively high priority toward reducing regulated emissions will lead to policies that favor scrapping old cars and replacing them with new models.
5.5. Sensitivity of results

The optimal fleet distributions determined in this study depend heavily on the characteristics of the baseline fleet. In order to examine the sensitivity of the analysis, the EMFAC2000 and ORNL survival curves are used to describe the baseline fleet. Table 1 compares the optimal production of new cars and the emission savings in the ideal fleet conversion scheme based on different survival rate scenarios. The overall trends of the ideal fleet conversion remain unchanged across the survival curves; accelerated vehicle retirements will increase life cycle CO\(_2\) emissions and energy, but will reduce overall life cycle CO, NMHC, and NO\(_x\) emissions.

For the regulated emissions, the optimal production and emission reductions based on the EMFAC2000 and ORNL survival rates are greater than those based on the MOBILE6 survival rates, because the survival rates of older cars are higher in the EMFAC2000 and ORNL estimates. As a result, more scrapping of high-emitting old cars and production of cleaner new cars to replace them are required to optimize overall fleet emissions than with the MOBILE6 survival curve. However, the MOBILE6 survival curve, which is a snapshot of a particular calendar year,

<table>
<thead>
<tr>
<th>Survival rate scenarios</th>
<th>Optimal new car production for different pollutants (emission savings compared with baseline fleet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO(_2)</td>
</tr>
<tr>
<td>MOBILE6(^a)</td>
<td>100 (0.0%)</td>
</tr>
<tr>
<td>EMFAC2000</td>
<td>100 (0.0%)</td>
</tr>
<tr>
<td>ORNL</td>
<td>100 (0.0%)</td>
</tr>
</tbody>
</table>

It is assumed that 100 new vehicles have been produced each year between 1981 and 2000.

\(^a\) See Fig. 8 for the results based on the MOBILE6 survival rate scenario.
may be more appropriate for this study than the other survival curves based on specific model years. The optimal fleet conversion policy minimizes the total life cycle emissions from all vehicle age cohorts in a fleet during a specific calendar year. Differences among survival rates are relatively insignificant factors in determining a long-term fleet conversion scheme where new car production is limited to 120 cars (20% increase).

For modeling purposes, the fleet optimization model introduced in this study simplifies the real-world fleet conversion process by making several assumptions. In the real world, the mileage driven by retired vehicles will be replaced by mileage driven by more than one vehicle age cohort, rather than simply by mileage driven in newly manufactured vehicles. Optimal new car production and emission savings for regulated emissions will be more moderate if VMT driven by multiple age cohorts (including many middle aged vehicles), rather than exclusively VMT in the newest vehicles, replaces the high-polluting VMT of retired cars. A study of the benefits of scrappage programs reveals that emission reductions from scrapping old vehicles vary significantly depending on the particular assumption about redistribution of mileage from retired vehicles across the remaining age cohorts (Deysher and Pickrell, 1997).

It is assumed that vehicles are scrapped from the oldest age cohorts until one cohort is exhausted, although a real-world scrappage policy would instead scrap a range of adjacent age cohorts simultaneously. This assumption, however, would probably have only a small impact on the optimal fleet conversion policies estimated.

6. Discussion

Efforts to reduce automotive emissions have been implemented in both engineering and policy domains. In spite of significant progress in reducing CO, HC, and NO\textsubscript{x} from new vehicles when measured in certification tests, air qualities in some urban areas are far from satisfactory, since a large fraction of emissions originate from the malfunctioning of emission control of older vehicles, as well as from off-cycle driving (Ross et al., 1995). Accelerated scrappage programs are an attempt to reduce these emissions by recruiting and scrapping old, high-polluting vehicles with some compensation paid to the vehicle owners. Although different in their forms and the size of incentives offered, such policies have been adopted in European countries such as France and Italy, as well as to a limited extent by various local governments in the US. It is important to note that scrappage programs might be only temporarily effective, since expected improvements in the durability of emission controls are likely to reduce malfunctions among the oldest vehicles in the future fleet. However, the incidence of malfunctioning emission controls among the newest vehicles is uncertain.

While the goals of scrappage programs also include boosting new car sales (Stoffer, 2002), surprisingly, few analyses have considered the environmental impact from additional car production and sales (Wee et al., 2000). This study explicitly takes into account the environmental burdens from the production of additional new vehicles. According to the simulation results of this study, new car production will create significant CO\textsubscript{2} emissions and consequently, scrapping vehicles younger than 20 years and producing more vehicles will result in a net increase of CO\textsubscript{2} emissions, although this increase is relatively small. This is mainly a result of the failure to significantly reduce CO\textsubscript{2} emissions over recent model years.
In the same manner, regulated emissions associated with vehicle production increase due to accelerated vehicle scrapping. However, as demonstrated by the simulations, net regulated emissions would be reduced by retiring vehicles at certain ages younger than 20 years old, depending on the specific pollutant. This contrasting result can be attributed to the frequent failures of emission controls for early model years and, on the other hand, significantly lower emission factors and greater reliability of emission controls expected to occur for future model year vehicles.

Caution must be used when applying this study to a specific scrappage scheme, since this study uses average emissions for each vehicle age and model year. The main targets of scrappage programs have been for vehicles over 10 years old in European countries, and over 15 years old in North America (Environmental Defense Fund and General Motors Corporation, 1998). However, some vehicles are identified as eligible for scrappage programs after failing inspection and maintenance tests. Malfunctioning vehicles generally emit significantly more than the average emissions among vehicles of the same model year and mileage group. Therefore, if the emissions were properly measured, malfunctioning vehicles could be more reliably identified, and scrappage programs could be more effective in reducing regulated emissions than indicated by this study.

In the simulations of optimal long-term fleet conversion allowing for an increase in production from 100 to 120 units dramatic changes in the composition of fleet are observed. A period of 15–20 years, depending on the specific pollutant, is required to return to the original fleet age distribution after a period of accelerated-scrapping and extra-production. According to the simulation results, a limited range of model years will be disproportionately represented in the fleet during this period, while older vehicles are being retired. The increased size of a model year cohort may lower the price of the model and conversely, reduced size of a model year cohort may raise the price of the model. Consequently, the rarity of old cars can raise the reimbursement price that program operators must offer to recruit cars to be scrapped (European Conference of Ministers of Transport, 1999). This might affect the economic viability of the simulated long-term fleet conversion scenario. However, this study does not pursue any economic cost and benefit analysis for a fleet conversion, mainly due to the complexity and uncertainty of these vehicle market mechanisms.

This study highlights major differences in scrappage programs based on greenhouse gas and local regulated emissions. The simulation shows, particularly for the regulated pollutants, that the nature of the trade-off likely depends on the economic valuation method used. The control cost estimates for reducing emissions of pollutants are generally larger than the corresponding damage cost estimates, sometimes by an order of magnitude. The estimated values by these two methods are compared for some major US cities in various studies (US Congress, 1992; Wang and Santini, 1994; Small and Kazimi, 1995). The estimation method can be chosen based on the purpose of the study, the decision-maker’s preference, and data availability. In addition, damage and control costs for regulated emissions are likely to vary with geographical locations. For example, large metropolitan areas may have a greater need to support scrappage programs due to the high damage costs for regulated emissions, and the comparatively high costs of achieving further reductions in their emissions. On the other hand, isolated small municipalities and rural areas would be likely to support retaining older vehicles in service to avoid the increase in greenhouse gas emissions from vehicle retirement and manufacturing, since the slightly higher levels of regulated emissions are not likely to reduce air quality significantly in these locations.
7. Conclusion

The aim of this study is to optimize fleet conversion policy based on life cycle emissions of mid-sized generic vehicles. According to the simulation results obtained, accelerated-scrapping and extra-production policies are effective for abating regulated emissions, but may do so at the expense of slightly higher emissions of greenhouse gases. On the other hand, retaining the current fleet age distribution without accelerated scrapping is the optimal policy from the standpoint of CO₂ emissions. In this regard, optimal fleet conversion strategies are dependent on the relative importance of each pollutant, and estimated damage and control costs for different pollutants vary with several factors, including the methods of estimation and geographical conditions. This implies that each scrappage program should be carefully designed based on the scale and target pollutants of the program.

Major determinants of optimal fleet conversion policies include the emission distributions among vehicle life cycle phases; the future emission scenarios associated with regulatory and technological progresses; and emission control deterioration or increases in failure probabilities with vehicle mileage. Controlling these determinants can affect the optimal fleet conversion policies. For example, a tighter fuel economy policy than the current scenario would support an accelerated scrappage program for CO₂, and eliminate or mitigate the trade-off between the regulated pollutants and CO₂. Caution must be exercised, however, when analyzing the effectiveness of policies using the present model due to the complicated feedback between determinants. For example, this analysis holds true only when the improved fuel economy can be achieved with negligible increment of CO₂ emissions from vehicle production.

Acknowledgements

This research was supported by the US National Science Foundation under the 1999 Technology for a Sustainable Environment program, grant No. BES-9985625. The authors thank Kevin Cullen and Ronald Williams for providing valuable information for this study.

References


