MARKET SYSTEMS MODELING FOR PUBLIC VERSUS PRIVATE TRADEOFF ANALYSIS IN OPTIMAL VEHICLE DESIGN

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Mechanical Engineering)
in The University of Michigan
2009

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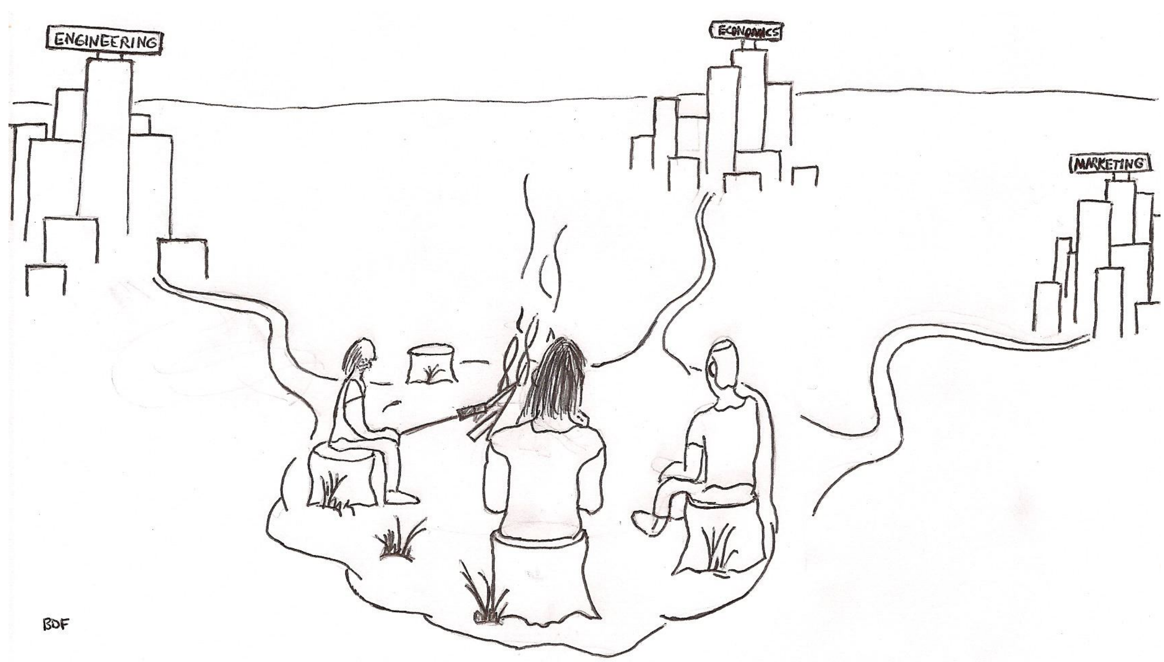
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ACKNOWLEDGEMENTS

I first acknowledge the overwhelming support of my family, especially my wife Carol, over the five years of graduate school. Many thanks to everyone in the Optimal Design Lab for their friendship and support. A very special thanks to Katie Whitefoot, Deokkyun Yoon, W. Ross Morrow, and Kevin Bolon for their unique contributions to my thinking, to the computational aspects of the work, and for organizing and providing much of the automotive data used in the dissertation. I also thank the members of my committee for their valuable feedback, suggestions, and encouragement along the way. I especially appreciate the financial, intellectual, and personal support of my advisor, professor Papalambros. His expectation of excellence is perhaps the most valuable learning I take away from my PhD experience.

I acknowledge and thank Maritz Holdings Inc. for use of the Maritz Research 2006 New Vehicle Customer Satisfaction survey data. This work has been supported by Ford Motor Company through the Ford-University of Michigan Innovation Alliance. The opinions expressed are only those of the author.

PREFACE

At first blush a dissertation with the words "market systems" in the title appears out of place in the mechanical engineering department. The dissertation is motivated by two observations. The first is that establishing the product development problem as I have posed it requires engineering insight. The goal here is to make product design decisions endogenous to the overall product planning decision. Achieving this goal requires the ability to model the technology capability of the firm. This is precisely what engineers do: describe the physical interactions within a product that lead to the complex attribute colinearities lamented by marketers and economists.

The second observation is that engineers are the primary customers of this work. The benefits from the insights gained from a market system approach that includes the ability to change vehicle design are most valuable in the early stages of product planning. At the early stage planners have the most design freedom. A methodology for exploring the potential economic desirability of future technologies provides insight into R&D investment. Additionally, integrating engineering design models in a market system context begins to provide tools to engineers to enable communication with the broader product development organization. As communication across the organization improves, the expected outcome is improved profitability, product quality, and reduced time to market.

BF

Ann Arbor, 2009

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Δ_{X_s}	The sensitivity metric for the Pareto set defining the change in the value of one objective with respect to the change from the nadir to the ideal value of the other objective
Γ	Portion of the choice share derivative with respect to price as defined in Equation (5.16)
$\mathbf{\Gamma_v}$	The coupling vector derived from the KKT optimality conditions for a weighted-sum objective for a system design problem
Λ	Portion of the choice share derivative with respect to price as defined in Equation (5.16)
Φ	The area metric for a Pareto set defined as the area of the rectangle that inscribes the Pareto Set
ω_r	Cost model coefficient for cost model parameter r
α	Product attributes observed by consumers
β	Fixed coefficients for product attribute and demographic interactions for individual i and product j that enter the utility expression with fixed effects
δ	Fixed coefficiencts for product attributes that enter the utility expression with fixed effects
ϵ_{ij}	Independent and identically distributed random variable that represents a portion of the random component of utility for individual i for product j
ε_{ij}	Random component of utility
γ	Combined OEM and dealer profit margin
κ	Effective curvature of the Pareto frontier that defines the relative convexity or concavity of a particular tradeoff
λ	The products of the choice-share derivatives
λ_n	The scaling parameter used for the area and sensitivity Pareto set metrics

μ Random coefficiencts for product attributes and product and demographic interactions for individual i and product j that enter the utility expression with random effects

ν_{ij} Systematic component of utility for consumer i for product j

ϕ The constraint decoupling ratio indicating the ratio of the angle where constraint decoupling exists and the angle between the objective gradients

π Single period profit

ρ^2 Likelihood ratio index

$\theta^<$ The polar cone angle between two objective gradients

ω_{ABS} Empirical cost model parameter coefficient for anti-lock brakes

ω_{AWD} Empirical cost model parameter coefficient for all wheel drive or 4 wheel drive vehicle

ω_{CDI} Empirical cost model parameter coefficient for common-rail direct injection fuel injection system

$\omega_{C_{Lvan}}$ Empirical cost model parameter coefficient for large cargo van

$\omega_{C_{mvan}}$ Empirical cost model parameter coefficient for small cargo van

$\omega_{EDisp_{CI}}$ Empirical cost model parameter coefficient for compression-ignition engine displacement

$\omega_{EDisp_{SI}}$ Empirical cost model parameter coefficient for spark-ignition engine displacement

ω_{Eng1} First cost parameter coefficient for spark ignition engine cost formula

ω_{Eng2} Second cost parameter coefficient for spark ignition engine cost formula

ω_{Eng3} First cost parameter coefficient for compression ignition engine cost formula

ω_{Eng4} Second cost parameter coefficient for compression ignition engine cost formula

ω_{HEVcon} HEV powertrain cost calibration constant

ω_{HEVm} Multiplicative constant on all HEV powertrain costs

ω_{Man} Empirical cost model parameter coefficient for manual transmission

ω_{SC} Empirical cost model parameter coefficient for vehicle stability control feature

$\omega_{T_C I}$ Empirical cost model parameter coefficient for turbo-charged compression-ignition (diesel) engine

$\omega_{T_S I}$ Empirical cost model parameter coefficient for for turbo-charged or twin turbo-charged spark-ignition (gasoline) engine

ω_{VCUV} Empirical cost model parameter coefficient for crossover vehicle size

ω_{VLSUV} Empirical cost model parameter coefficient for large sport utility vehicle size

$\omega_{VLpupLvan}$ Empirical cost model parameter coefficient for large pickup or large van vehicle size

ω_{VLxSUV} Empirical cost model parameter coefficient for Luxury SUV or crossover vehicle size

ω_{VMSUV} Empirical cost model parameter coefficient for midsize sport utility vehicle size

ω_{VSpup} Empirical cost model parameter coefficient for small pickup truck vehicle size

ω_{Vmvan} Empirical cost model parameter coefficient for minivan vehicle size

ω_{con} Empirical cost model parameter coefficient for constant parameter

ξ The angle between two objective gradients

$4WD$ Four wheel drive

$\mathcal{A}$ The attainable set of objective values in a multiobjective optimization problem

AWD All wheel drive

$\mathbf{b}_{ij}$ Product attribute and demographic interactions for individual i and product j that enter the utility expression with fixed effects

B_{ik}^{m} The partial derivative of utility for individual i with respect to X_k^m of product k

$b_{m \cdot c}$ Minivan and children in household interaction dummy variable

$BMEP$ Brake mean effective pressure

$b_{p \cdot r}$ Pickup truck and rural living interaction dummy variable

$b_{s \cdot c}$ SUV and children in household interaction dummy variable

c Product unit cost

c_{avg}	Per vehicle unit variable cost for average vehicle
c_{bod}	The variable cost per unit of the body
c_{chas}	The variable cost per unit of the chassis
c_{CIEng}	Cost component from the compression ignition engine for empirical cost model
C_f	Total fixed cost for manufacturer
c_{fun}	The hypothetical variable cost to produce a single unit of the average vehicle given the specified learning curve effect
$c_{fun,bod}$	The hypothetical variable cost to produce a single unit of the body for an average vehicle given the specified learning curve effect
$c_{fun,chas}$	The hypothetical variable cost to produce a single unit of the chassis for an average vehicle given the specified learning curve effect
$c_{fun,pwtrn}$	The hypothetical variable cost to produce a single unit of the powertrain for an average vehicle given the specified learning curve effect
$c_{fun,whe}$	The hypothetical variable cost to produce a single unit of the wheels for an average vehicle given the specified learning curve effect
c_{HEV}	Total unit variable cost for the HEV powertrain components
c_{HEVB}	Cost for battery for HEV powertrain
c_{HEVBC}	Cost for brackets and cables for HEV powertrain
c_{HEVcon}	Cost for controller for HEV powertrain
CI	Subscript used to indicate a compression-ignition or diesel engine
C_j	Product total production cost
c_j	Per vehicle unit variable cost
$c_{j,a}$	The assumed unit vehicle cost based on a given markup relationship between the OEM and the dealer
c_{MG1}	Cost for electric machine 1 for HEV powertrain
c_{MG2}	Cost for electric machine 2 for HEV powertrain
c_{pwtrn}	The variable cost per unit of the powertrain
c_{SIEng}	Cost component from the spark ignition engine for empirical cost model
c_{whe}	The variable cost per unit of the wheels

D	The total number of draws for each individual i from the distributions of the random attribute partworths $\boldsymbol{\mu}$
d_{Chr}	European brand dummy variable
d_{Eur}	European brand dummy variable
d_{GM}	European brand dummy variable
$\mathbf{d}_j$	Product attributes for product j that enter the utility expression with fixed effects
d_{Jap}	European brand dummy variable
d_{Kor}	European brand dummy variable
$E_{ijX_k^m}$	The elasticity of demand for individual i for vehicle j is the percentage change in demand for j given a percentage change in attribute m of vehicle k
$E_{jX_k^m}$	The elasticity of demand for vehicle j is the percentage change in demand for j given a percentage change in attribute m of vehicle k
F	The total number of firms competing in the market
f	Subscript representing an individual firm $1, \ldots, F$
$\mathbf{f}^\circ$	The ideal or utopia point; the vector of ideal values for all criteria
f_{MPG}°	Ideal value for fuel economy for a given design optimization problem
f_{MPG}^N	Nadir value for fuel economy for a given design optimization problem
f_n°	The ideal value for objective f_n. In other words the optimum for objective f_n solved as a single objective problem
f_n^N	The nadir value for objective f_n. In other words the worst value for objective f_n that is also some Pareto point $\mathbf{f} = [f_n^N, f_l]$
FWD	Front wheel drive
f_{yj}	A dummy variable equal to 1 when for choice observation y product j is selected and $f_{yj} = 0$ otherwise
G	The combined gradient norm for the price equilibrium problem defined to be the L_∞-norm of the vector composed of the products of the choice-share derivatives $\boldsymbol{\lambda}$ and the difference between the initial prices and computed fixed-point prices $\mathbf{p} - \mathbf{q}$
g	Inequality constraint

GTDI — Gas turbo direct-injection engine

G_{tol} — The convergence tolerance for the combined gradient norm as defined in Equation (6.6)

H — Learning curve effect; value of 1 represents no learning

h — Equality constraint

HEV — Hybrid electric vehicle

I — The total number of individuals in a sample population

i — Subscript representing an individual consumer $1, \ldots, I$

J — The total number of individuals in a sample population

j — Subscript representing an individual product $1, \ldots, J$

J_f — The total number of products j designed by firm f

L — Likelihood function

L_{ij} — The conditional likelihood individual i chooses vehicle j for a particular μ_i

L_{∞} — The L-infinity norm taken to be the maximum value from a vector of values

LL — Log-likelihood function

M — Total market size

m_{CUV} — Crossover vehicle class dummy variable

$\mathbf{m}_{ij}$ — Product attribute and product and demographic interactions for individual i and product j that enter the utility expression with random effects

$m_{LpupLvan}$ — Large pickup truck or large van vehicle class dummy variable

m_{LSUV} — Large sport utility vehicle class dummy variable

m_{LxSUV} — Luxury sport utility or crossover vehicle (all sizes) class dummy variable

m_{MSUV} — Midsize sport utility vehicle class dummy variable

m_{mvan} — Minivan vehicle class dummy variable

m_{pup} — Pickup truck vehicle class dummy variable

m_{Spup} — Small pickup truck vehicle class dummy variable

$MSRP$ — Manufacturer suggested retail price. This value is used to represent the price paid by the consumer

m_{SUV}	Sport utility vehicle class dummy variable
m_{tsmc}	Two seater or minicompact vehicle class dummy variable
m_{van}	Full size van vehicle class dummy variable
n	Subscript representing a specific objective criterion $1, \ldots, N$
OEM	Average operating leverage, which is the relative distribution of fixed versus variable costs
OEM	Original equipment manufacturer. In the context of this dissertation, OEM signifies a automobile producer such as Ford or Toyota.
p_{avg}	The average vehicle price for vehicles in the considered class used in the scaling cost model
P_{ij}	The unconditional likelihood individual i chooses vehicle j
P_j	Choice share for product j
p_j	Product unit price
$\mathbf{Pl}$	Matrix of choice shares where each row represents an individual from a population and each column represents a vehicle alternative
$\mathbf{p}'$	The computed fixed-point prices
P_{peak}	Peak engine power output
P_{tol}	A tolerance value indicating the minimum magnitude of the choice probability for a given vehicle in order for it to get updated by the fixed-point iteration
p_{tol}	The convergence tolerance for changes in price during the single-stage design and price equilibrium game computation
q	The total number of designing firms
Q_{avg}	The sales volume of the average vehicle
$\mathbf{Q}^{\geq}(\mathbf{x})$	Points in the decision space that are inferior to $\mathbf{x}$
Q_j	Quantity demanded for product j
$\mathbf{Q}^{<}(\mathbf{x})$	Points in the decision space that are superior to $\mathbf{x}$
$\mathbf{Q}^{\sim}(\mathbf{x})$	Points in the decision space that are not comparable to $\mathbf{x}$
R	Product total revenue
r	Product quality

r Subscript representing a cost parameter $1, \ldots, R$

r_{stol} The tolerance for the minimum improving stepsize in the fixed-point algorithm for the price equilibrium calculations

RWD Rear wheel drive

$\mathbf{s}$ Individual demographics

$\mathcal{S}$ The set constraint for design variables

SI Subscript used to indicate a spark-ignition or gasoline engine

s_{inc} Individual annual income

SI Spark-ignition gasoline engine

S_j The observed choice share for product j from the data sample

U_{ij} Utility of consumer i for product j

$\mathbf{v}$ model parameters assumed fixed during design optimization

v_{4WD} Dummy variable for four wheel drive

v_{AWD} Dummy variable for all wheel drive

v_{CD} Vehicle coefficient of drag

v_{cI} Nominal peak current for HEV powertrain

v_{cm} Mass of a single battery cell for HEV powertrain

v_{cQ} Nominal battery cell charge for HEV powertrain

v_{cV} Nominal battery cell voltage for HEV powertrain

v_{Dies} Dummy variable for diesel engine

$v_{EDTBc_3^*}$ Baseline $EDTBc_3$ value for HEV powertrain

v_{FWD} Dummy variable for front wheel drive

v_{G1} Transmission gear ration for first gear

v_{G2} Transmission gear ration for second gear

v_{G3} Transmission gear ration for third gear

v_{G4} Transmission gear ration for fourth gear

v_{H156} Vehicle minimum ground clearance

v_{HEV} Dummy variable for hybrid electric vehicle powertrain

$v_{K_{BM}}$ Scaling coefficient affecting spread in battery costs based on changes in the specific energy of the battery with respect to the reference battery

v_{MCC^*} The reference manufacturing cost in dollars per kg, for batteries given the reference specific energy

v_{MMPG} Parameter value indicating the minimum allowable fuel economy for a given design optimization problem

v_{MRW} Engine mounting midrail width

v_{MSH} Minimum required driver sitting height

v_{pay} Vehicle minimum payload capacity

v_{RWD} Dummy variable for rear wheel drive

v_{TC} Dummy variable for turbo-charged engine

v_{tw} Tire width

$v_{tw,avg}$ The average tire width for vehicles in the considered class used in the scaling cost model

v_w Wheel diameter

$v_{w,avg}$ The average wheel diameter for vehicles in the considered class used in the scaling cost model

W_r Cost model parameter r

W_{ABS} Empirical cost model parameter for anti-lock brakes

W_{AWD} Empirical cost model parameter for all wheel drive or 4 wheel drive vehicle

$W_{C_{Lvan}}$ Empirical cost model parameter for large cargo van

$W_{C_{mvan}}$ Empirical cost model parameter for small cargo van

W_{CDI} Empirical cost model parameter for common-rail direct injection fuel injection system

W_{con} Empirical cost model parameter for constant parameter

$W_{EDisp_{CI}}$ Empirical cost model parameter for compression-ignition engine displacement

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W_{VLSUV}	Empirical cost model parameter for large sport utility vehicle size
W_{VLxSUV}	Empirical cost model parameter for Luxury SUV or crossover vehicle size
W_{VMSUV}	Empirical cost model parameter for midsize sport utility vehicle size
W_{Vmvan}	Empirical cost model parameter for minivan vehicle size
W_{VSpup}	Empirical cost model parameter for small pickup truck vehicle size
$x_{W105,avg}$	The average vehicle width for vehicles in the considered class used in the scaling cost model
W_{HEVBpk}	Battery per kilogram cost for HEV powertrain
w_n	Weighting value for objective f_n
$\mathbf{x}$	Design variables
$\mathcal{X}$	Feasible design domain
x_B	Engine bore diameter
x_{BPow}	Peak power output for hybrid electric vehicle battery pack
x_{BtS}	Engine bore to stroke ratio
x_{FD}	Final drive ratio
x_{H101}	Vehicle total height as a design variable
$x_{H101,avg}$	The average vehicle height for vehicles in the considered class used in the scaling cost model
x_{L101}	Vehicle wheelbase as a design variable
$x_{L101,avg}$	The average vehicle wheelbase for vehicles in the considered class used in the scaling cost model
x_{L103}	Vehicle total length as a design variable

$x_{L103,avg}$	The average vehicle length for vehicles in the considered class used in the scaling cost model
X_k^m	The value of attribute m for vehicle k
x_{PGR}	Planetary gear ratio
X_s	The scaled difference between the nadir and ideal values for the first objective function
x_{W105}	Vehicle total width as a design variable
y	Subscript representing a choice observation $1, \ldots, Y$
Y_s	The scaled difference between the nadir and ideal values for the second objective function
$\mathbf{z}$	Product performance criteria
z_{060}	Time for vehicle to accelerate from 0 to 60 miles per hour time
z_{3050}	Time for vehicle to accelerate from 30 to 50 miles per while towing
z_{65T}	Maximum climbing grade at 65 miles per hour while towing
$z_{\$/mi}$	Dollars per mile fuel cost for a specific vehicle and price of gas
z_{A107}	Angle of departure from rear wheel to rear bumber
z_{A147}	Ramp breakover angle between front and rear wheels
z_{CAh}	The stored charge per battery cell in Amp-hours for HEV powertrain
z_{CE}	The energy storage capacity of a battery cell for HEV powertrain
z_{CGlong}	Vehicle center of gravity in longitudinal direction
z_{CGvert}	Vehicle center of gravity in vertical direction
z_{CS}	Underhood crush space between bumper and driver heel point
z_{CVI}	Cargo volume index measured behind 2nd row
z_{EDisp}	Engine displacement
$z_{EDisp,avg}$	The average engine displacement for vehicles in the considered class used in the scaling cost model
z_{EDTBc_3}	Energy density of a battery cell in Watt-hours per kilogram for HEV powertrain
z_{EL}	Engine length

z_{GVWR} Gross vehicle weight rating

z_H Vehicle total height

z_{hp} Peak engine horsepower

z_L Vehicle total length

z_{MCS} Minimum calculated required underhood crush space

z_{MD} Deceleration in 35 miles per hour frontal crash

z_{MG1} Peak power output for motor-generator one

z_{MG2} Peak power output for motor-generator two

z_{MPG} Combined city and highway fuel economy

z_{NC} Number of battery cells for HEV powertrain

z_{Roll} Vehicle rollover score

z_{TF} Tire flop, distance in the width direction to allow tire movement

z_{tol} The convergence tolerance for changes in vehicle attributes during the two-stage design and price equilibrium game computation

z_{TS} Vehicle top speed

z_{VM} Vehicle mass, also known as curbweight

z_W Vehicle total width

ABSTRACT

Market Systems Modeling for Public Versus Private Tradeoff Analysis in Optimal Vehicle Design

by

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Chair: Panos Y. Papalambros

The motivating application for this work is the tension between the public versus private tradeoff in the automotive industry between firm profit and the public negative externalities of automotive transportation, particularly fossil fuel energy use and greenhouse gas emissions.

This dissertation establishes a methodology for evaluating automotive vehicle design according to private (firm profit) and public (fuel consumption) criteria. The methodology set forth relies on developments from engineering, economics, and marketing. The primary contribution of this dissertation is that these disparate developments have been brought together in a single mathematical problem formulation for a large-scale problem. The integrated problem formulation will allow study of interdisciplinary issues related to product development in a new way. Other work has begun to develop similar comprehensive problem formulations. This work points to some of the challenges that must be addressed in such formulations. Specifically, the functional form of the cost models, and the utility specification of the demand models can have a large impact on the market outcomes even when the differing models ap-

pear to fit the underlying data similarly well. A second contribution is the application of the notion that we can explore the tradeoff between private interests and public interests by simulating market response under different hypothetical scenarios. We can then gain deeper insights by examining the tradeoff relationships between the different scenarios.

The strength of the approach, at its current state of development, lies not in a claim to predict future automotive market behavior but in establishing a quantitative approach for evaluating the implications of future scenarios were they to become reality. Individual firms and policy makers can learn from this approach by comparing the differences between the scenario outcomes.

The problem formulation integrates models of demand, cost, and product performance in order to implement a game-theoritic formulation of producer behavior where producers choose the attributes of the products they produce and the prices they will charge in order to maximize profit. Two variations of a newly estimated mixed-logit discrete choice model of new car buyer purchase behavior are developed for incorporation as demand models. Three cost model formulations are developed and compared in the context of the problem formulation. An explicit representation of an automotive manufacturer's technology capability in the form of a comprehensive yet stylized engineering performance model is developed. Novel metrics are established for comparing the Pareto set of solutions from one hypothetical scenario to the next. Hypothetical scenarios are evaluated involving the design of a single vehicle within a price-equilibrium market context and the design of multiple same-segment vehicles within a price-equilibrium market context. The differences in scenario outcomes based on differences in the demand and cost models are explored. The results show that improving the fuel economy of a specific vehicle does not always lead to a reduction in US fleet fuel consumption.

Several areas for modeling improvement are identified.