

Automotive Features: Mass Impact and Deployment Characterization

by

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B.S. Electrical Engineering, Massachusetts Institute of Technology,
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Submitted to the Engineering Systems Division
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Abstract

Passenger car use is a major driver of greenhouse gas (GHG) emissions and fossil fuel consumption in the United States. Vehicles continue to incorporate increasing levels of technology, these advances do not translate directly into improved fuel economy. Vehicle weight, interior volume and performance have all grown substantially in the past 30 years, as has feature content.

This thesis shows that safety features, emissions controls, and optional equipment account for a total mass that mirrors growth in vehicle mass during this time period. Chief among these are optional features designed to improve the comfort and convenience of passenger cars.

This thesis also examines historical deployment rates of vehicle features. Safety features and emissions controls achieve faster deployment rates than other optional features. While these features are those most governed by regulation, it is not clear that regulations push technology deployment rates higher. Automotive product development is complex and features require significant time to overcome deployment constraints. This lag time, from first production use to most rapid deployment across the vehicle fleet, is found to be exponentially decreasing for all feature types and has dropped to approximately a decade.

These analyses provide two countering assessments. New vehicles will continue to grow heavier due to the continued incorporation of new features, but technology that may improve overall efficiency can be brought to market ever faster.

Thesis Supervisor: Professor John B. Heywood
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List of Acronyms and Common Terms

ABS Anti-lock Brakes

BAU Business As Usual, a term used to describe a modeling scenario where present conditions are presumed to carry forward unchanged.

BEV Battery Electric Vehicle

BMEP Brake Mean Effective Pressure

CAFE Corporate Average Fuel Economy, the sales-weighted average fuel economy of the vehicles produced by a manufacturer in a given year.

CARB California Air Resources Board

Criteria Pollutant Six common air pollutants regulated by the U.S. EPA: Ozone, Particulate Matter, Carbon Monoxide, Nitrogen Oxides, Sulfur Dioxide and Lead.

DOT U.S. Department of Transportation

EIA Energy Information Administration

EISA Energy Independence and Security Act

EPA U.S. Environmental Protection Agency

EPCA Energy Policy Conservation Act

ERFC Emphasis on Reduction of Fuel Consumption

ESC Electronic Stability Control

Feature Equipment on a vehicle not strictly necessary for basic vehicle functionality but required by law to improve safety or emissions, or optionally added by automakers to improve the comfort, convenience or consumer appeal of a vehicle.

FI Fuel Injection

FMVSS Federal Motor Vehicle Safety Standard

GHG Greenhouse Gas

ICE Internal Combustion Engine

LDV, Light Duty Vehicle Passenger cars and light trucks with a gross vehicle weight under 8,500 lbs

MPG Miles per gallon

MSRP Manufacturer's Suggested Retail Price

NHTSA U.S. National Highway Traffic Safety Administration

NPRM Notice of Proposed Rulemaking

OEM Original Equipment Manufacturer

PHEV Plug-in Hybrid Electric Vehicle

PSFI Performance-size-fuel economy index

SI Spark-Ignition, generally referring to gasoline-powered engines

SUV Sport Utility Vehicle

Take Rate The percentage of new vehicles or passenger cars equipped with a specific feature in a given year.

VMT, VKT Vehicle Miles Traveled, Vehicle Kilometers Traveled: An expression for the average distance traveled by each vehicle in a given fleet.

VVT Variable Valve Timing

Chapter 1

Introduction

Chapter 1

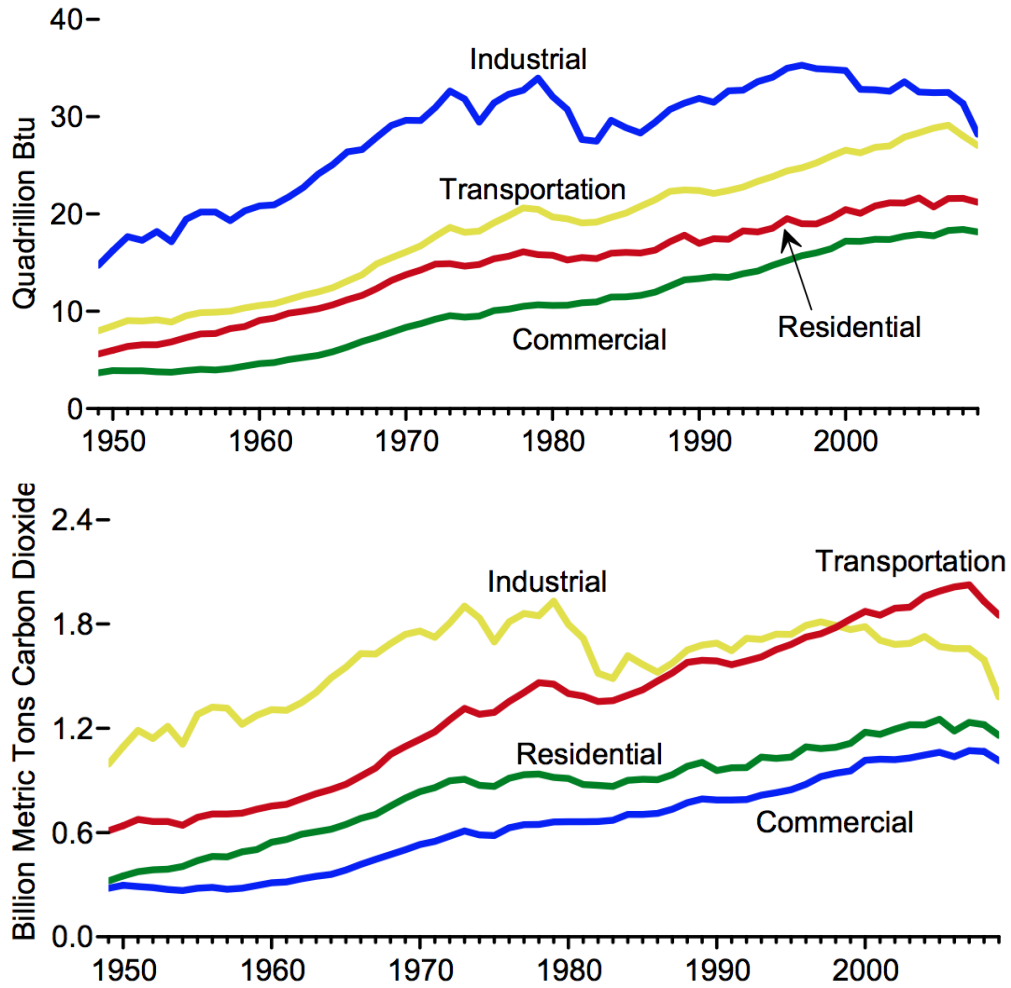
Chapter 1 outlines the importance of transportation in petroleum and GHG contexts, discusses the importance of vehicle features in the evolution of the passenger car, and outlines the themes to be discussed in the remainder of the document.

For nearly a century the automobile has been the dominant form of personal transportation in the United States. The passenger car has made inexpensive, reliable transportation accessible to virtually every citizen and has profoundly affected the development of modern society.

At the same time, transportation has also become a dominant source of greenhouse gas (GHG) emissions and fossil fuel consumption in the United States. As shown in Table 1.1, the Transportation sector represents a growing driver of energy and fossil fuel use. The Transportation sector is now responsible for 71% of petroleum consumption and 34% of GHG emissions. Since 1999 the Transportation sector has exceeded the Industrial sector as the largest emitter of greenhouse gases.[EIA, 2010]

The Transportation sector derives 94% of its energy from Petroleum. 45% of this petroleum is used to produce motor gasoline, the vast majority of which is used to fuel Light Duty Vehicles (LDVs). The GHG emissions and fossil fuel consumption driven by the Transportation sector have been modeled by numerous groups.

Table 1.1: Data from EIA showing historical energy consumption and GHG emissions by sector.



The fundamental factors driving such consumptions are shown below, adapter from [MIT, 2008].

$$GHG_{emissions} = LPK * VKT * FI$$

Where,

$GHG_{emissions}$ = Greenhouse Gas Emissions (tons/year)

LPK = Liters per Kilometer (L/100km)

VKT = Vehicle Kilometers Traveled (VKT in km/year)

FI = GHG intensity of Fuel (GHG tons/liter of fuel)

While there are interactions among these factors, LPK is the only factor here reliant on the technical sophistication of vehicles themselves while FI and LPK are primarily a product of infrastructure and usage.

1.1 Vehicle Evolution

During its development over the past century the passenger car has evolved from a rudimentary, self-propelled "horseless carriage" to a sophisticated device capable of traveling hundreds of miles at high speeds. All new vehicles sold in the United States incorporate seat belts and at least two airbags; virtually all new vehicles include air conditioning and automatic transmissions to increase driver comfort and many also include navigation systems, moonroofs, and a bevy of other electronic aids.

Gains in performance, size and fuel economy are relatively straightforward to analyze, as these factors have been carefully tracked since 1975 in the EPA Fuel Economy trends report. As shown in Figure 1-1 below fuel economy grew rapidly from approximately 1977-1987 and has since remained relatively constant. Vehicle performance has continually increased since the mid-1980s and vehicle size, measured using interior volume, has also grown modestly over the same time period.

However, vehicle capability has improved in other ways as well. Vehicles are safer, emit fewer criteria pollutants per mile traveled, and include a broad array of equipment designed to improve dynamic capabilities provide the driver with a high level of comfort and information.

[Cheah, 2010] highlights the importance of vehicle features by comparing two vehicles: a 2008 Audi A4 and a 2006 Mazda3 Touring, as shown in Table 1.2. The two vehicles are nearly identical in performance, interior space, exterior dimensions and highway fuel economy. However, the Audi has a significantly longer list of standard equipment, performs better in several crash tests, is 50% more expensive and weighs 345 kg more than the Mazda. Cheah attributes the mass increase primarily to the higher feature content of the Audi. However, this is only a single data point: a closer examination is needed to address the fleet-wide impact of features on the mass of

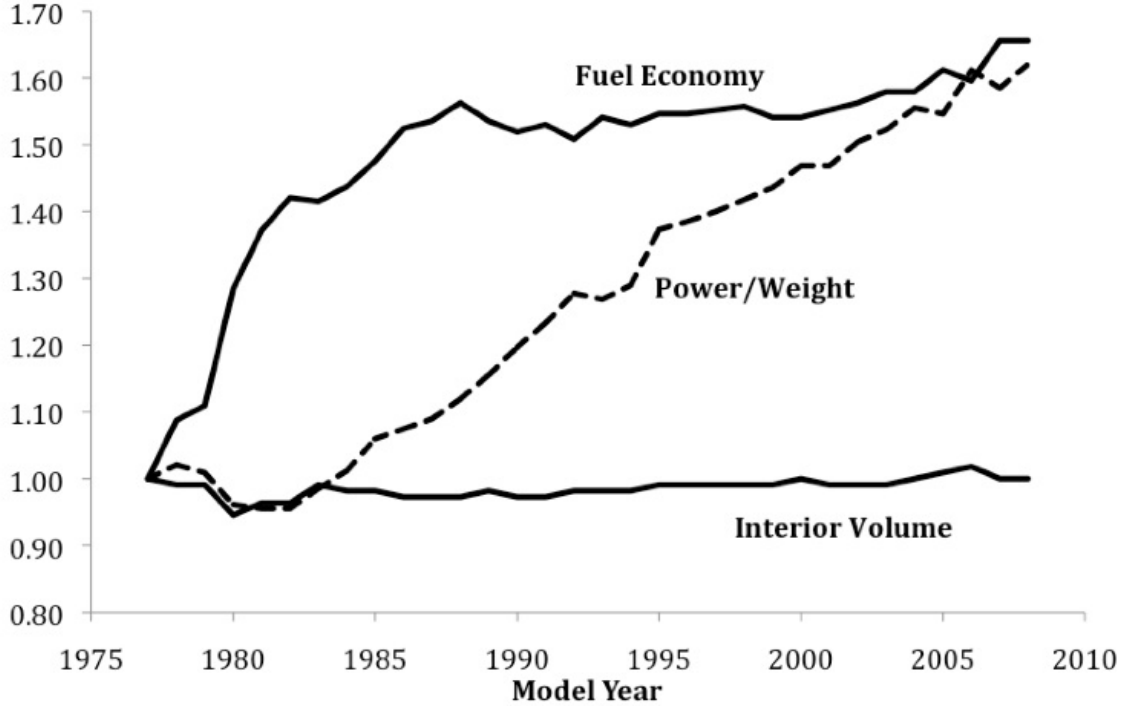


Figure 1-1: Average performance, size and fuel economy of new U.S. cars, 1977-2008, indexed to 1977 averages. Graphic from MacKenzie, 2009 using data from U.S. EPA, 2008

vehicles.



Figure 1-2 graphically illustrates four case studies of growth in the mass of vehicles of various classes.

1.2 Motivation

Existing work by [An and DeCicco, 2007, MacKenzie, 2009, Knittel, 2009] has investigated the tradeoffs among performance, size and fuel economy and consumer willingness to pay for said attributes. However, as shown by Cheah in the previous section, vehicles similar in these common metrics may still be substantially different in their ability to deliver functionality to the purchaser in the form of additional features. The need to quantify this tradeoff dimension has, to date, remained unfilled.

Performing an analysis of vehicle features pays dividends in other ways. While features such as fuel injection, multiple valves per cylinder and variable valve timing

Table 1.2: Audi A4 vs. Mazda3: A comparison of vehicles with similar primary attributes but very different features. Adapted from [Cheah, 2010].

Year, Model	2008 Audi A4 2.0T Quattro	2006 Mazda3 s Touring
		
Body style	4-dr sedan (seats 5)	4-dr sedan (seats 5)
Wheelbase	104.3 in	103.9 in
length x width x height	180.6 x 69.8 x 56.2 <i>in</i> ³	178.7 x 69.1 x 57.7 <i>in</i> ³
Overall volume (l*w*h)	11.61 <i>m</i> ³	11.68 <i>m</i> ³
Horsepower	200 hp	160 hp
Power-to-weight ratio	0.057 hp/lb	0.058 hp/lb
0-60mph (est.)	9.58 sec	9.59 sec
Engine displacement	2.0L I4	2.3L I4
Front head, leg room	37.9 in, 41.3 in	39.1 in, 41.9 in
Luggage capacity	13.4 <i>ft</i> ³	11.4 <i>ft</i> ³
City/hwy (adj.) fuel economy	22/31 MPG	26/32 MPG
Features	16" wheels, AWD, power seat adjustment, sunroof, heated mirrors, dual zone climate controls, 10 speakers + subwoofer, traction and stability control	17" wheels, FWD, manual seat adjustment, sunroof optional
NHTSA crash test ratings driver, passenger, side impact front, rear, rollover	4, 4, 5, 4, 4 stars	4, 4, 3, 3, 4 stars
MSRP	\$28,900	\$17,600
Curb weight	1,595 kg (3,516 lb)	1,251 kg (2,758 lb)

(VVT) are tracked by the U.S. EPA, the deployment rates of these features are not strictly the product of consumer demand and automaker ability to deploy such technology. To varying degrees each of these technologies has been driven by criteria pollutant regulations. Because of this, viewing the deployment of such features in the broader context of safety regulation-driven and optional features serves to better characterize deployment of technology in the automotive fleet.

1.3 Research Objectives

This thesis serves to address the following primary research questions described below.

Mass Impact What has been the impact of safety and emissions requirements and

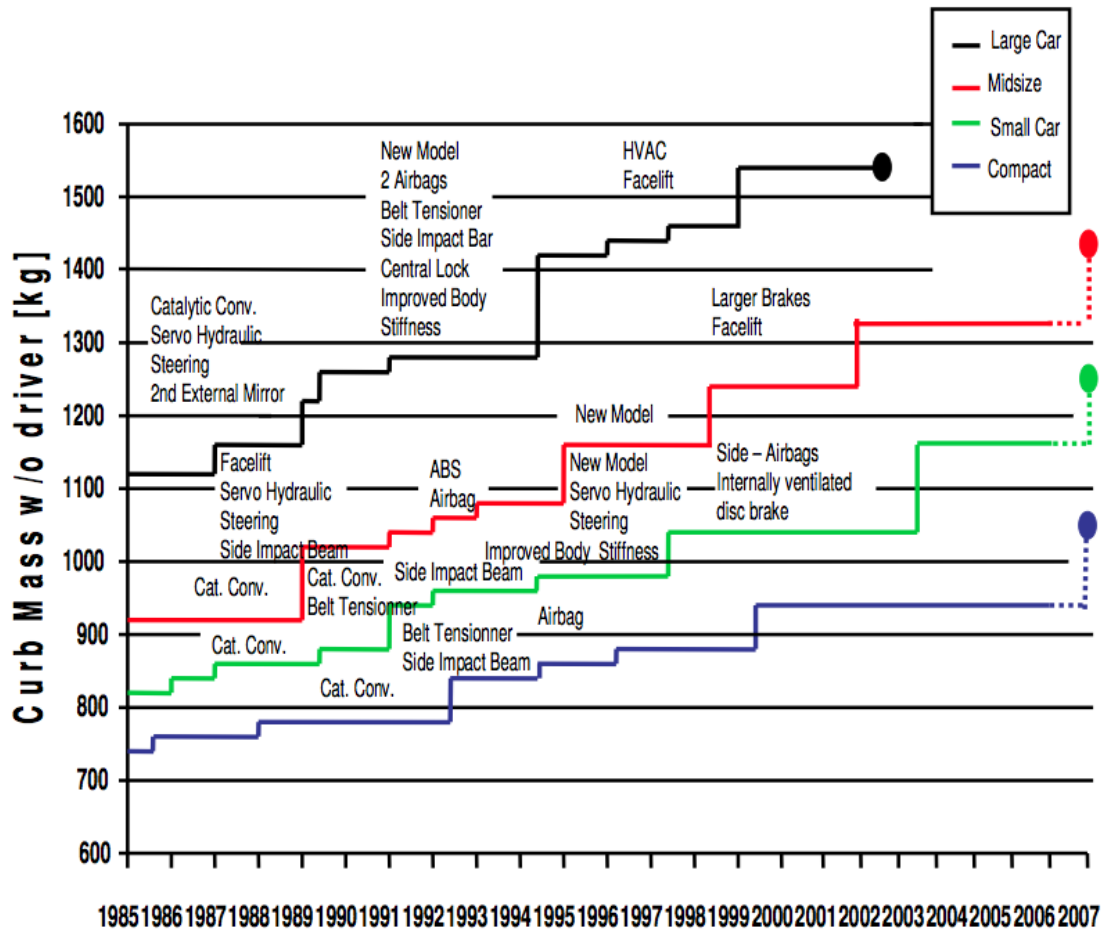


Figure 1-2: Growth in mass of vehicles from four major classes from [Glennan, 2007]

other optional features on the mass of automobiles in the United States?

Trends in Features What is the trend in deployment of features in each of these areas?

Technical Sophistication How can information about vehicle features be used to refine existing measures of technical sophistication?

Deployment Scenarios What do past trends in feature deployment rates tell us about possible future deployment of vehicle features?

1.4 Methodology and Comments

This thesis is composed of two distinct analyses. Chapter 2 combines estimated deployment data of vehicle features of three categories (safety equipment, emissions controls, and optional features) and estimated mass of each feature to calculate the total mass added to an average passenger car as a result of this equipment.

Chapter 4 analyses the characteristics of the deployment of vehicle features for which time series deployment data is available and identifies key parameters in the historical deployment of approximately 35 unique vehicle features at fleet-wide and manufacturer levels.

1.4.1 Data Sources

Estimates of mass impact of legally mandated safety features are drawn directly from analysis performed by NHTSA in DOT HS 809 834.[DOT, 2004a]. This study addresses both the deployment rate of specific features and their weight contribution year-over-year. Learning effects are addressed: vehicles from a range of dates are torn down and the mass contribution from each NHTSA regulation is individually addressed.

Specific equipment required for emissions controls from 1970 - 1990 has been interpreted from a timeline of EPA regulations [EPA, 2011]. The mass contributions from each of the regulations during this period are drawn from vehicle teardown data discussed below.

Take rates of some optional features is drawn from Wards Factory Installed databases. [Ward's, 2010b, Ward's, 2010a]. Of the 74 optional features analyzed, 34 of these features had historical take rate data available. Where option take rates are unavailable, yearly take rates have been estimated based on feature introduction dates and availability on top-selling 2010 vehicles as discussed in Chapter 2. Of the forty features estimated using this linear method, half resulted in estimated take rates of less than 10% and with a minimal mass impact.

The mass of each vehicle feature is approximated by summing the masses of indi-

vidual vehicle components attributed to the application of a specific feature. Confidential component-level teardown data, including mass, is provided by an unnamed OEM for four individual passenger cars (two compact and two full-sized). For twenty-five of these features, mass was calculated as an average value of the applicable equipment from these four vehicles. Where mass data for individual features is unavailable, an estimated value has been used. Of the features where estimated mass was used, twenty-four were on features with estimated take rates of less than 10% with minimal overall impact.

1.4.2 Limitations

Over the course of their development many features incorporate improvements that result in their implementation with a reduced mass (i.e. electric power steering vs. hydraulic power steering). [DOT, 2004a] incorporates a learning effect the mass of specific safety features by tearing down two vehicles a specific number of years apart and assumes a linear reduction in mass over the intervening years. All other features are assumed to have a constant mass over time. This assumption is the result of limitations on data availability. Vehicle teardown data for every year is not available, so component mass values from 2010 vehicles have been used to determine feature weights.

Since the teardown data used for the purposes of this analysis is at a component level, only components that can be directly attributed to a specific feature are included. For example, weight values used for power seats include only the switches, motors and harnesses identified separately in the data set. Gearboxes or other structural changes to the seats in order to accommodate power assistance are not included. Because not all components of every system are composed of individually identifiable parts, the mass values for optional features calculated by this analysis could reasonably be called a *lower bound* of the possible range of masses of a given optional feature. This is distinct from the concept of secondary mass, discussed in Chapter 2, which refers to mass resulting from reinforcing other systems to maintain vehicle performance.

While light trucks represent an increasingly large share of new vehicle sales (40% in 2009), the use and makeup of the light truck fleet has changed dramatically. Light trucks, originally envisioned primarily as work vehicles, now include SUVs and crossover vehicles that have replaced passenger cars in private use. Since it would not be practical to isolate demographic groups among light truck purchasers, the analysis performed in this document focuses strictly on passenger cars and does not include information on light trucks.

Chapter 2

Vehicle Features

Chapter 2

Chapter 2 dissects the increasing presence of features into those improving safety, reducing emissions, and those offering luxury amenities. This chapter further quantifies the resultant mass increase in the passenger car fleet and proposes estimates of how fleet fuel consumption might change in the absence of these features.

2.1 Definitions

For the purposes of this thesis, a feature is defined as any component that is not strictly necessary for the basic functionality of the vehicle but that is either required by legal mandate or advertised as providing a benefit to the consumer.

In this section features are categorized as Safety, Emissions, or Optional. Safety and Emissions equipment are strictly required components as defined by respective governing agencies. Components with driver and passenger safety implications that are not currently mandated, such as rollover airbags and park distance control are classified as optional equipment for the purposes of mass impact, but are classified as safety features in Chapter 4. Table 2.1 identifies how features have been classified for the purposes of this analysis.¹

¹In this analysis, both curtain airbags and anti-lock brakes are identified as optional features.

Table 2.1: Examples of feature categorization.

Optional Features	Safety	Emissions
Automatic Transmission	Power Brakes	Catalytic Converters
Power Steering	Frontal Airbags	Evaporative Emissions Controls
Int. Wiper / Washers	Child Seat Anchors	EGR valves
Air conditioning	Side Door Beams	Fuel injection

2.2 Context

Following a decline in the late seventies and early eighties, the average mass of passenger cars in the United States has climbed steadily as shown in Figure 2-1. While some of this mass increase is attributable to a modest growth in interior volume over the same time period, a large portion of this growth in mass is the result of features that improve the safety, emissions, and comfort/convenience of modern vehicles.

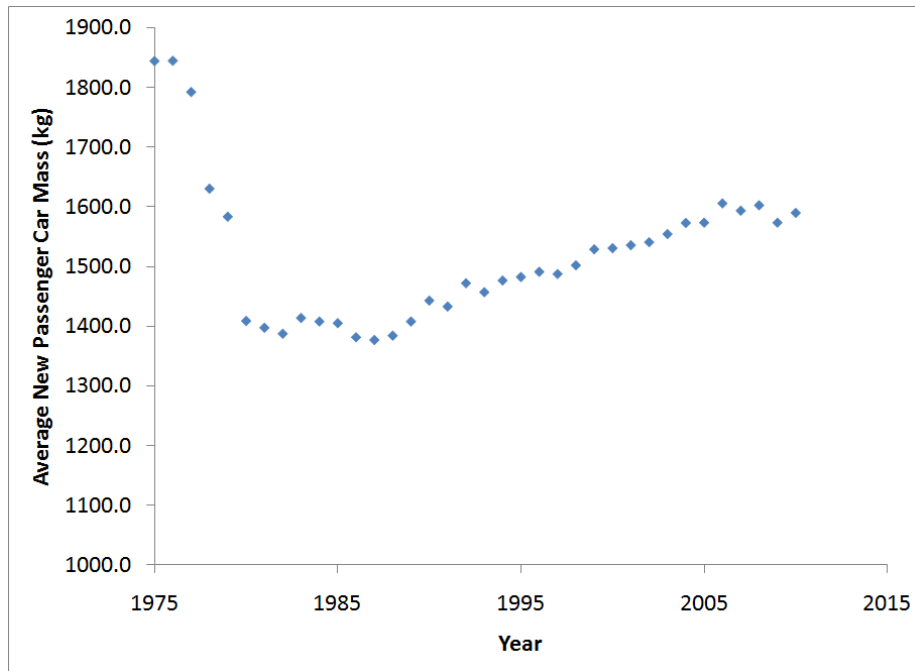


Figure 2-1: The average mass of passenger cars in the United States has climbed since the mid-1980s. Source: [EPA, 2010]

This chapter proposes a framework for estimating the mass increase in modern

However, both of these features will soon become required safety features. Anti-lock brakes, a component of most Electronic Stability Control systems, are being phased in from 2009-2012 in compliance with FMVSS 126. Proposed legislation requiring curtain airbags under FMVSS 208 was issued during the writing of this document and is yet to be finalized.

vehicles that is the result of comfort/convenience features and also identifies estimates of mass attributable to regulations governing safety and emissions. Secondary mass estimates (defined in Section 2.6) are applied and the results of these estimates are summed to produce overall mass impact of features.

These calculations serve two primary purposes. First, using these estimates of feature mass we can estimate what the mass of current production vehicles might be without the presence of these additional features. Second, since the feature content of vehicles continues to grow, we can extrapolate trends in vehicle equipment to predict the mass of features in future vehicles.

2.3 Safety Features

Modern vehicles incorporate a vast array of technologies to reduce the likelihood of injuries and fatalities in the event of a crash. Advanced materials strengthen critical areas around vehicle occupants, seat belts reduce the likelihood of ejection, and airbags control occupant deceleration rates. New ways to protect occupants are constantly under development, and the National Highway Transportation Safety Administration (NHTSA) continually reviews available technologies. When it deems appropriate, NHTSA issues a ruling mandating that all vehicle incorporate new technologies.

In 2004 NHTSA compiled a report [DOT, 2004a] that quantified the mass added to passenger cars and light trucks as a result of the cumulative impact of safety regulations from 1968-2001. According to this report, 2001 model year passenger cars were, on average, 57 kg (125.44 lbs) heavier as a result of these regulations. While a subsequent report has not been released, a regression of this data suggests that weight attributable to NHTSA regulations has risen to 62 kg (136.4 lbs) in 2010 as shown in Figure 2-2 below and, if current trends are maintained, would exceed 100 kg (220 lbs) by 2050.

This analysis incorporates only features that are explicitly mandated by NHTSA requirements but were not in widespread use prior to regulation. For example, rear window defoggers, although now required, were already in widespread use at the time

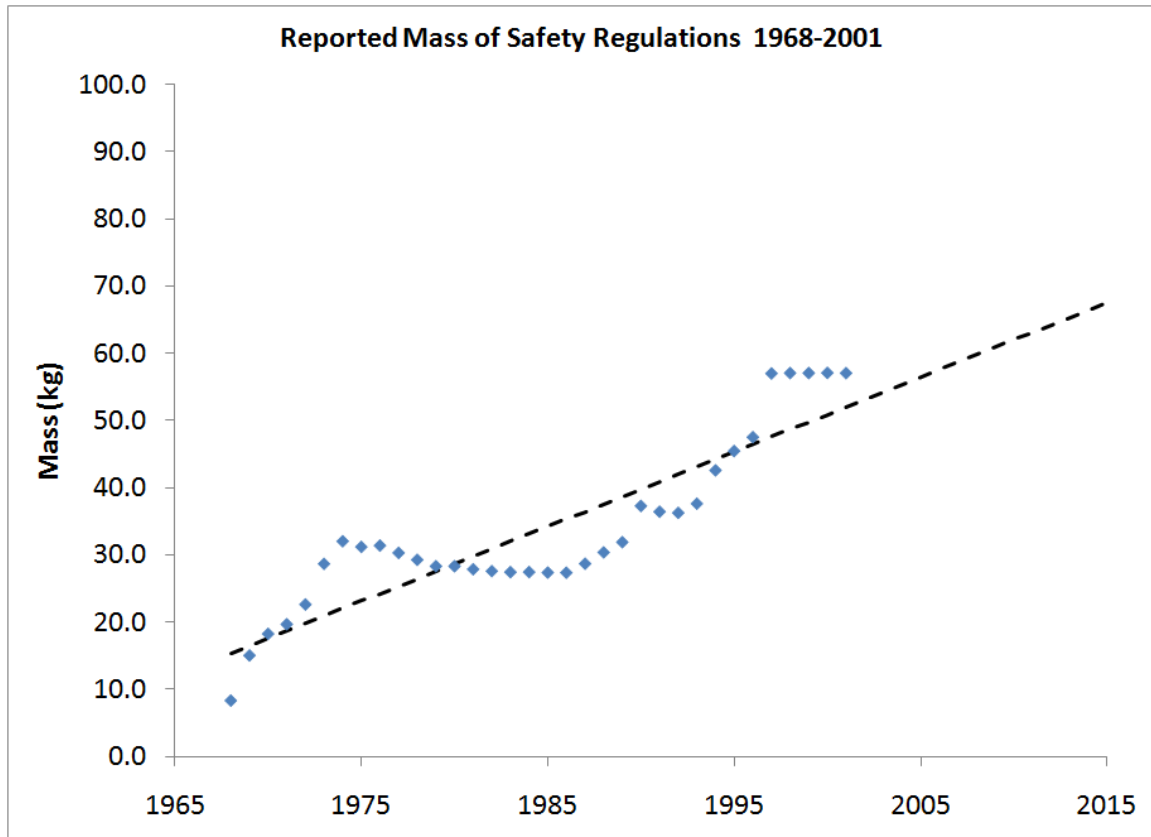


Figure 2-2: Average mass added by safety regulations from 1968-2001 as reported by U.S. DOT in report HS 809 834.

the regulation governing them was issued and are not included here.

Other features that have an impact on safety are classified as optional features for the purposes of this analysis. For example, while NHTSA does not specifically track driveway incidents as they occur on private property, [NHTSA, 2011] and [Safe Kids USA, 2011] discuss the large number of children involved in such incidents each year. Ultrasonic parking assistance (Park Distance Control) and rearview cameras have the potential to reduce the number of such accidents. Since NHTSA regulations are frequently updated, features such as this may become required equipment in the future. In the meantime, however, they are classified as optional.

2.4 Emissions Controls

Since the first Clean Air Act in 1970, the Environmental Protection Agency has introduced a series of regulations governing automotive emissions of *criteria pollutants*. However, the EPA has not published a report that performs a tear-down analysis of the cumulative impact of its legislation comparable to the work published in DOT report HS 809 834.

To simulate the results of a comprehensive teardown report this thesis identifies individual vehicle components attributable to EPA regulations in the Bill of Materials (BOM) of four typical passenger cars and then allocates the average mass to specific regulatory milestones from 1970 - 1990 published by the EPA on its webpage.[EPA, 2011] The allocation of these specific technologies to the milestones was confirmed as plausible in an interview with an EPA staffperson in 2010. A summary of this analysis is shown in Table 2.2.

Table 2.2: Emissions control legislation with associated components and mass.

Date	Regulation	Components Introduced	Estimated Mass (kg)
1970	Clean Air Act	PCV (Positive Crankcase Ventilation) valves and early evaporative canisters.	1.75
1972	NOx Standards	EGR (Exhaust Gas Recirculation) Valves	0.42
1975		First generation catalytic converters	4.17
1981	Amended Clean Air Act	3-way catalytic converters	4.17
1990	Clean Air Act	Enhanced evaporative emissions controls and electronic engine management	3.03
1994-1997	Clean Air Act "Tier I"	various	
1994	Clean Air Act Amendments	On board diagnostics	
1994-2003	CARB LEV I	various	
1999-2003	Transitional NLEV Program	various	
2004-2009	Clean Air Act "Tier II"	various	
2004-2010	CARB LEV II	various	

As shown in Table 2.2 the EPA is not the only body regulating automotive emis-

sions in the United States. Since 1990 the California Air Resource Board (CARB) has introduced a series of regulations under the Low Emissions Vehicle (LEV) program. Under the Clean Air Act, other states are permitted to adopt either Federal standards or those set by CARB.

Since regulations may now only apply to vehicles sold in certain states, identifying the vehicle mass attributable to exclusively to emissions controls has become far more complex. To further complicate matters, the technologies used to meet these regulations (such as variable valve timing, multiple valves per cylinder, and direct injection) offer other benefits such as improved drivability and performance. From the EPA Tier 2 FRM Regulatory Impact Assessment[EPA, 1999]:

In addition to gains in breathing, the multiple-valve (typically 4-valve) design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) which decreases the distance the flame must travel inside the chamber. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing combustion efficiency which lowers engine-out HC emissions.

and

Variable valve timing can allow for increased swirl and intake charge velocity, especially during low load operating conditions where sufficient swirl and turbulence tend to be lacking. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions.

.

As a result it is not appropriate to ascribe the mass increase from these technical changes exclusively to emissions regulations.

Since estimating the additional mass of emissions equipment beyond 1990 is quite complex, for the purposes of this analysis a linear regression has been performed on

the mass increases identified from 1970 - 1990 and extrapolated. The resultant mass increase values have been discussed with EPA staff members who agreed the values are plausible.

Figure 2-3 shows the calculated mass of emissions equipment from 1970-1990 and the projected trend based on a linear regression of values during this time period. By 1990, approximately 13.6 kg of emissions equipment had been added to the average passenger car. Regression suggests that by 2010 this value has nearly doubled to 24.6 kg per passenger car.

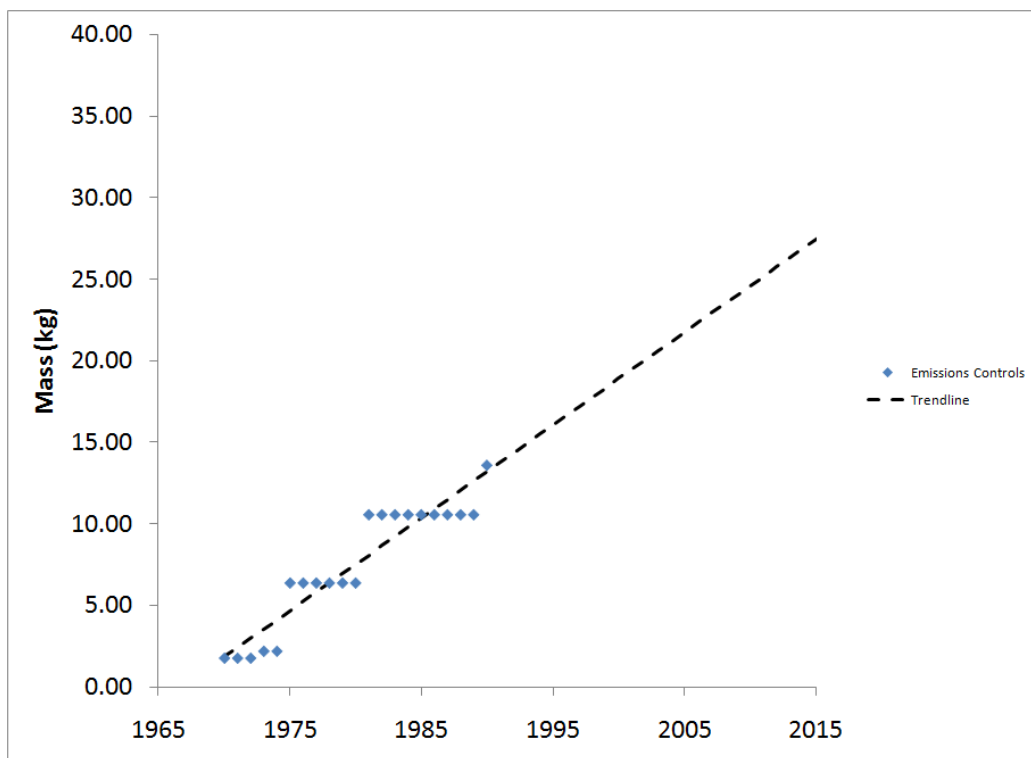


Figure 2-3: Estimated mass of emissions control equipment by year.

It is questionable whether a linear extrapolation of past trends is a reasonable assumption, and it could be argued that the shift from criteria pollutant regulations to GHG emissions regulations could lead to mass reductions through material selection and advanced design in an effort to meet GHG reduction targets. However, it is also possible that GHG reduction requirements will necessitate the deployment of BEVs with large battery packs and lead to an increasing mass requirement attributable to

such regulations. In the absence of an alternative, a linear extrapolation has been used.

2.5 Optional Features

Most new cars sold in the U.S. are equipped with a large number of features designed to improve the comfort of passengers or provide additional information to the driver. Air conditioning, automatic transmissions, radios and other features are present in virtually every passenger car sold today, and dozens of other features are equipped at lower rates. A full list of features and their availability on top-selling 2010 passenger cars is shown in Appendix A.

Since not all cars are equipped with all features, the average mass added to each new vehicle on average by n features is determined according to the following equation:

$$Mass_{features} = \sum_{i=1}^n (mass_i) * (takerate_i)$$

The take rate (the percentage of new cars in a given year equipped with a feature) of many features is tracked by Ward's Automotive in its Factory Installed equipment databases. [Ward's, 2010b, Ward's, 2010a] The data provided by Ward's Automotive are sales-weighted take rates

For features that are not tracked by Ward's data, yearly equipment rate is based on the *availability* of features on top-selling vehicles in early 2010 and the introduction date of the feature as shown in the formula below. This formula assumes strictly linear growth rather than the S-curve shaped growth shown to be typical, but since only two data points are used (date of introduction and take rate in 2010) it is not reasonable to generate an S-curve.

$$Takerate_{2010} = .85 * V_{standard} + .25 * V_{optional} + .01 * V_{unavailable}$$

Where $V_{standard}$ is defined as the number of top ten selling vehicles that include said

feature standard, $V_{optional}$ is the number of top ten selling vehicles that offer said feature as an option, and $V_{unavailable}$ is the number of top ten selling vehicles that do not offer the feature at all.

Table 2.3: An example of vehicle feature availability in 2010. S = feature is standard in all trim levels; O = feature is optional or available on some trim levels; N = feature is not offered on this vehicle.

Feature	Toyota Camry	Toyota Corolla	Honda Accord	Honda Civic	Nissan Altima	Ford Fusion	Chevrolet Impala	Chevrolet Malibu	Ford Focus	Toyota Prius
Center Console / Armrest	S	S	S	O	S	S	S	S	N	S

Since many features are included standard and certain trim levels, a feature is said to be standard only if it is included on all trim levels. Using the example taken from Table 2.3, $V_{standard} = 8$, $V_{optional} = 1$ and $V_{unavailable} = 1$ for the feature Center Console/Armrest in 2010. As a result, the take rate for 2010 would be determined to be $(8 * .85) + (1 * .25) + (1 * .01) = .68 + .025 + .001 = 71\%$. The take rates for these features are assumed to grow linearly from the date of their first production, street-legal application.

Figure 2-4 shows the distribution in mass and take rates for the ten features with the highest impact in 2010. Relatively only two features (air conditioning and automatic transmission) have an impact of more than 5kg per car in 2010, but a large number of features with varying masses and take rates produce a fleetwide impact of 2-3kg per passenger car.

The cumulative additional mass from comfort and convenience features from 1975 - 2010 is shown in Figure 2-5. This analysis suggests that in 2010, the average passenger car was equipped with 136.1 kg in features. Project growth in the take rates of these features suggest that the mass impact would grow to 232.2 kg in 2050. This value includes only project growth in features already known and does not attempt to predict the impact of new features not yet available.

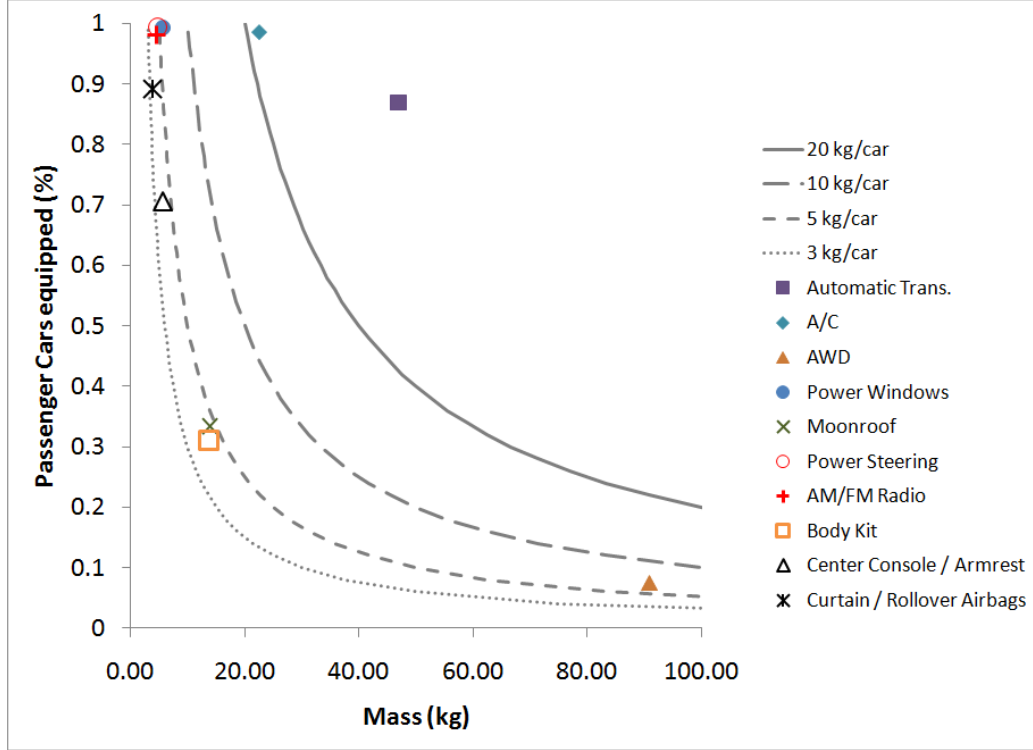


Figure 2-4: Mass and take rate of ten features with highest fleetwide impact. Lines of isometric fleet impact at levels of 20, 10, 5 and 3 kg/car are also shown.

2.6 Secondary Mass

Secondary mass is defined as the mass of additional components and structure necessary to support a primary component or system and maintain vehicle performance. For example, the primary mass of a sunroof system is contained in the sunroof cassette, drains, wiring harness and electronic modules necessary to operate it. Secondary mass for a sunroof system would be additional structural reinforcement, insulation and marginal engine and brake component growth necessary to offset the increased vehicle mass. Secondary mass is usually considered in the context of possible mass reductions but the reverse effect—secondary mass accumulation—is what is considered here.

A literature review by the Materials Systems Laboratory (MSL) at MIT of recent studies of secondary mass is shown in Appendix B. The Mass Decompounding Coefficient cited in the table refers to the percentage of primary mass attributable

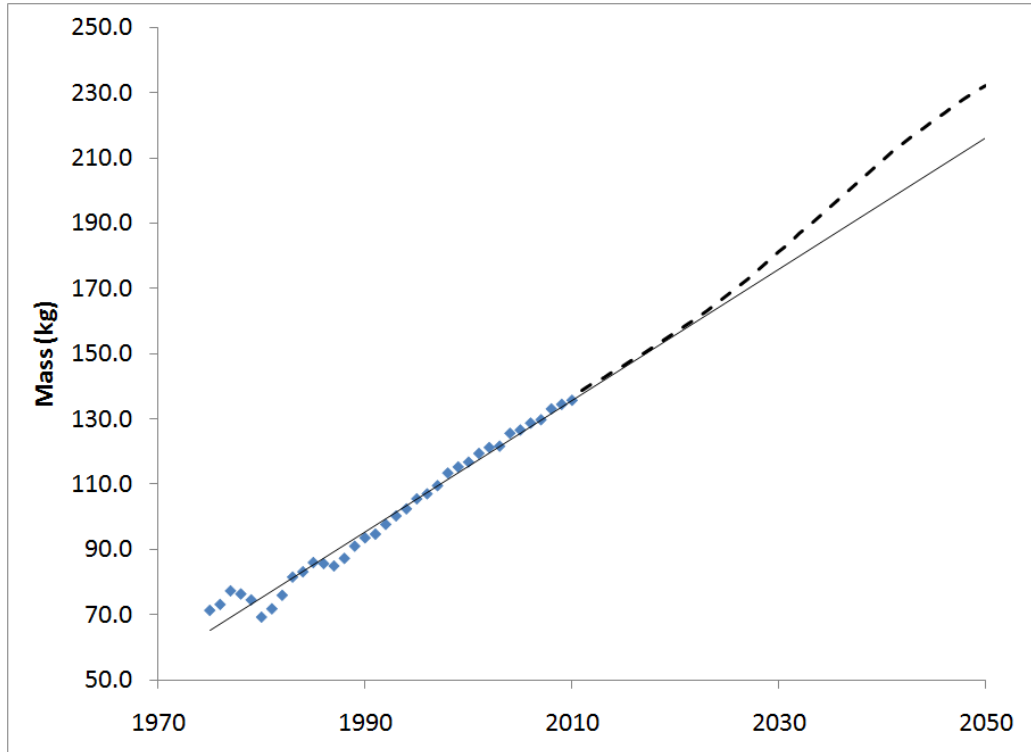


Figure 2-5: Estimated mass impact of optional features by year. Dashed lines show projected future impact using fits of existing take rate data, while solid line is a linear fit of historic data.

to secondary mass. For example, a mass decomposing coefficient of 50% would indicate that the study found for each kilogram of primary mass, 0.5 kg of secondary mass was identified.

As reported in the literature the coefficients cited in the table vary widely from 23-129%. A strict average of these studies results in a mass decomposing coefficient of 79.6%. Thus for the purposes of this analysis a secondary mass coefficient of 80% has been used.

Recent studies, such as those of the Materials Systems Lab at MIT, have narrowed focus to identify whether power train components are held constant or not. Where power train components are allowed to change, the mass decomposing coefficient is generally higher. However, the ability to incorporate power train changes into a vehicle design is typically a function of timescale: year-to-year power train components usually remain constant but during a vehicle refresh or facelift such changes would

be possible. Since this thesis identifies changes over decades on a fleet-average basis, such changes are abstracted out.

2.7 Conclusions

Figure 2-6 highlights the impact that vehicle features have had since 1975, incorporating a secondary mass value of 80% applied to each feature category.

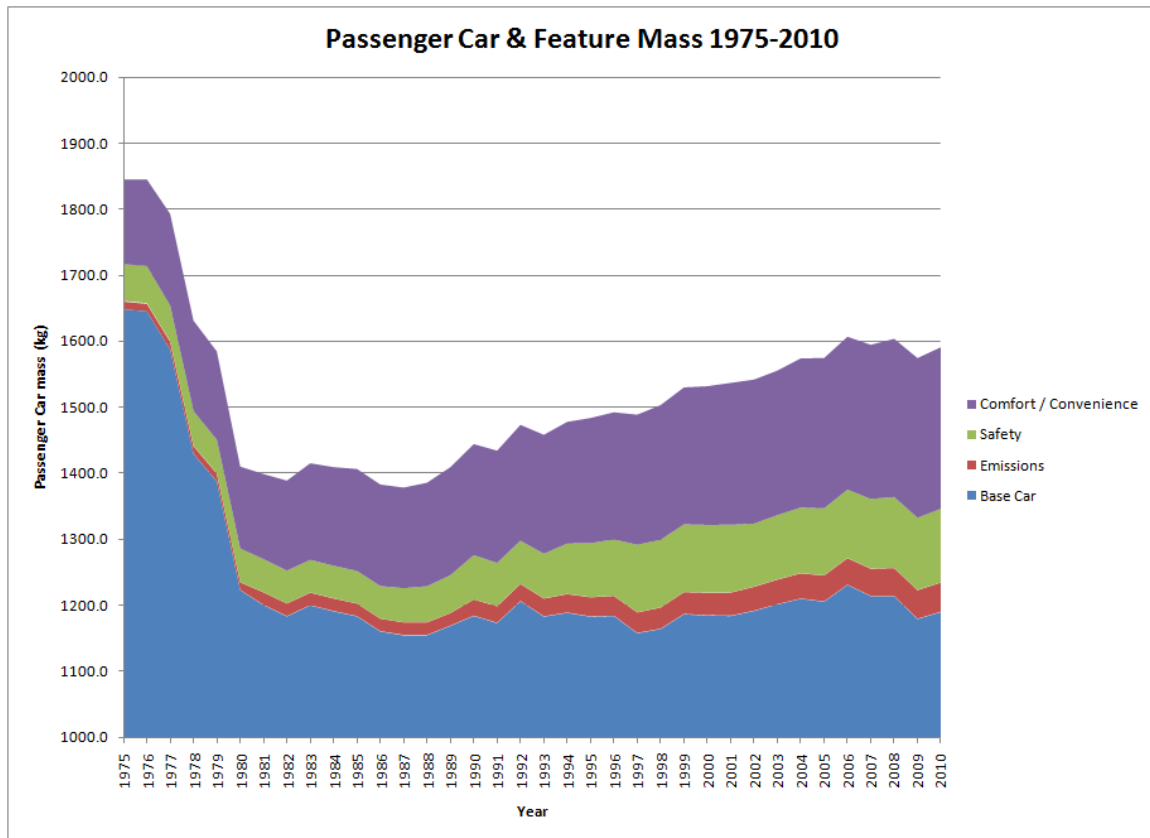


Figure 2-6: Mass of passenger cars 1975-2010 and weight attributed to Safety, Emissions and Comfort/Convenience features (Secondary mass included).

Required safety and emissions equipment are the source of approximately 62 kg (3.9%) and 24.6 kg (1.5%), respectively to a 2010 vehicle. On average, optional equipment added to new 2010 vehicles added more than 136 kg (8.6%) to 2010 vehicles. By comparison, 1975 vehicles on average incorporated 31.2 kg (1.7%) of safety equipment, 6.35 kg (0.3%) emissions equipment, and 71 kg (3.9%) of optional features.

According to this analysis, basic sales-weighted passenger car mass (average passenger car mass less mass attributed to features) was 1183 kg (2603 lbs) in 1982. This base mass actually continued to drop until a low of 1154 kg was reached in 1987. Basic vehicle mass has remained relatively constant, reaching a value of 1190 kg in 2010. Virtually all of the 200 kg in growth in vehicle mass since the mid-1980s is attributable to increasing adoption of vehicle safety, emissions, and comfort/convenience features.

Chapter 3

Measuring Technological Sophistication

Chapter 3

Chapter 3 reviews existing methods used to estimate vehicle technological sophistication. This chapter further uses the estimates of mass devoted to features to inform these estimates.

This chapter discusses a variety of measures of technical sophistication and their relatively consistent growth over time. Brake Mean Effective Pressure (BMEP) is a measure of technical efficiency, while the Performance-Size-Fuel Economy Index (PSFI), developed by An & DeCicco (2007), is a measure of the ability to deliver measurable amenities to consumers.

Neither is a perfect measure: technical efficiency is a relatively foreign concept to most car buyers and improvements in thermal efficiency can be used to either generate greater horsepower or improve fuel economy. On the other hand, PSFI is unable to capture all attributes that are important consumers and therefore underestimates actual growth.

This chapter proposes incorporating vehicle features, using mass values identified in Chapter 2, into the PSFI metric. The resulting metric, *adjusted* PSFI, thereby more closely reflects customer-perceivable amenities.

3.1 BMEP

A common measure of internal combustion engine efficiency is Brake Mean Effective Pressure (BMEP). As discussed in [Chon and Heywood, 2000] and [Heywood and Welling, 2009], BMEP is a measure of the brake work per cycle an engine produces divided by the engine's displacement:

$$BMEP_{max} = \frac{4\pi * T_{max}}{V_d}$$

or can be expressed as a function of volumetric efficiency (η_V), fuel conversion efficiency ($\eta_{f,i}$) and mechanical efficiency (η_m) multiplied by the fuel to air mass ratio ($\frac{F}{A}$), intake/atmospheric air density ($\rho_{a,i}$) and fuel heating value (ϱ_{HV}):

$$BMEP = \eta_V \eta_{f,i} \eta_m \frac{F}{A} \rho_{a,i} \varrho_{HV}$$

In Figure 3-1 Heywood and Welling show that the BMEP of engines increased at a relatively constant rate of approximately 1.5% per year from 2000 - 2008, with slight variations between naturally aspirated and forced-induction engines. These measurements are not sales-weighted, but are derived from the engines *available* each year.

These results suggest that engines are becoming more efficient at a relatively constant rate. However, since BMEP is strictly a measure of engine efficiency it is silent on the issue of how the entire vehicle system might have developed due to advances in manufacturing technology, materials and design.

3.2 PSFI

The BMEP growth rate of approximately 1.5% per year shown by Heywood and Welling correlates well with the growth rate in ton*mpg, a unit used by the EPA to describe vehicle efficiency. An and DeCicco (2007), using data from [Heavenrich, 2006], calculate that ton*mpg increased an average of 1.6% per year from 1975 - 2005.

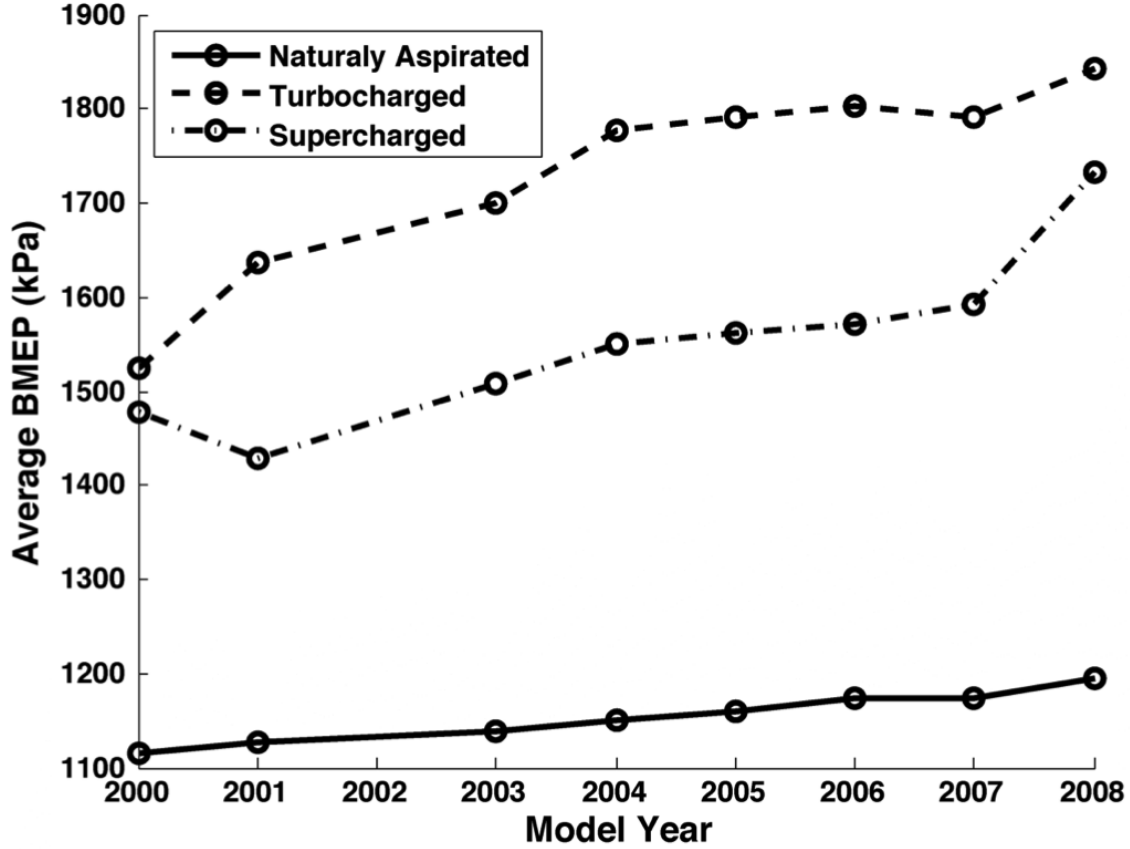


Figure 3-1: Trends in BMEP for U.S. engines from 2000 - 2008 [Heywood and Welling, 2009]

However, recognizing that ton*mpg does not incorporate growth in amenities such as size and performance, An and DeCicco (2007) introduce the concept of the Performance Size Fuel Economy Index (PSFI) as a measure of whole-vehicle sophistication based on readily measurable amenities.¹ For passenger cars PSFI is defined as:

$$PSFI = P * S * F = \frac{hp}{lb} * FT^3 * MPG$$

In words An and DeCicco describe this measure as "the ratio of moving a spatial carrying capacity a unit distance with a given performance capability per unit of fuel consumed." As shown in Figure 3-2, An and DeCicco, incorporating growth in all

¹An and DeCicco use the term amenities to describe desirable characteristics tracked by the EPA. This term should not be confused with the term *feature* used in this document to describe the addition of physical equipment to perform specific functions.

primary vehicle attributes tracked by the EPA, find that PSFI has grown at a rate of 5.3% for passenger cars from 1977 - 2005.

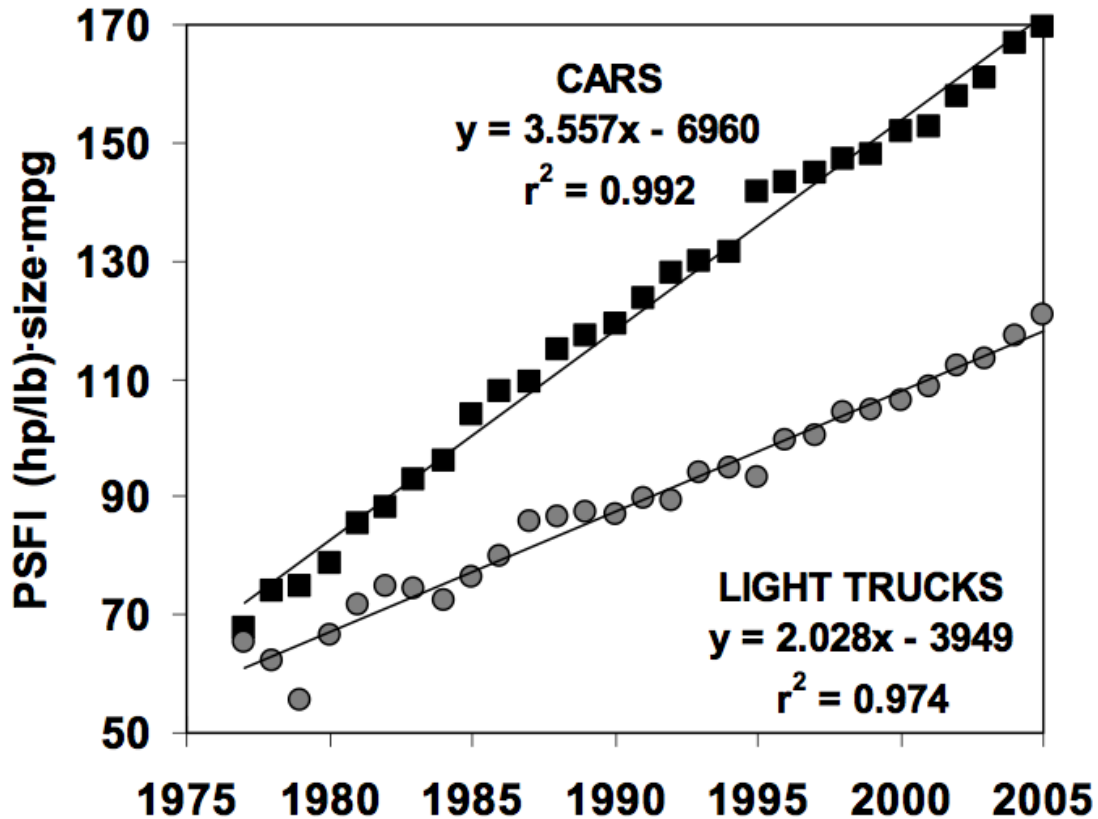


Figure 3-2: Performance Size Fuel Economy Index, 1975 - 2005 from [An and DeCicco, 2007]. This metric of vehicle sophistication has grown with remarkable linearity since 1975.

3.3 Adjusted PSFI

By incorporating three commonly measured attributes, PSFI is clearly a step closer to accurately representing a measure of the technical sophistication of modern vehicles. However, a critical omission of PSFI is that it is unable to capture developments in feature content that result in improved vehicle safety, reduced emissions and comfort/convenience.

As a quick illustrative example, take the values used for PSFI in 2005: 3463 lbs, 182 hp, 111 cu ft and 29.5 mpg. Assume that several years later car companies have, on average, added 346 lbs (10% of weight) of equipment to improve safety, emissions, and comfort/convenience of the vehicle fleet. Further assume that powertrains have improved sufficiently to increase horsepower 10% without any resulting decrease in fuel economy. The resulting fleet of vehicles—with an average weight of 3809 lbs and 200 horsepower but with identical interior volume and fuel economy—would clearly be more sophisticated than the vehicles that preceded them but the calculated average PSFI would be exactly the same.

To ameliorate such a shortcoming of PSFI, this paper proposes an *Adjusted* PSFI metric. Adjusted PSFI simply adds a fourth term to the PSFI that represents a ratio of vehicle mass *with* safety, emissions and comfort convenience features over the same vehicle without these features. The resultant $PSFI_{Adjusted}$ metric is as follows:

$$PSFI_{Adjusted} = P * S * F * \frac{Mass_{w/features}}{Mass_{w/oFeatures}} = \frac{hp}{lb} * FT^3 * MPG * \frac{lb}{lb}$$

Since this fourth term is unitless, the $PSFI_{Adjusted}$ metric has the same units as the standard PSFI metric. However, as shown in Figure 3-3, using the new metric we can see that technical sophistication has grown at a faster rate than that shown by PSFI.

3.4 Conclusions and Tradeoffs

These analyses indicate that the average technological sophistication of vehicles, measured by thermal efficiency of available engines, has grown consistently by a rate of approximately 1.5% per year since the 1980s. When determined by ability to deliver customer-perceivable amenities the growth is shown to be approximately 5.3% per year since 1977.

Both of these indexes are measures of average vehicle performance—BMEP referring to non-sales weighted availability and PSFI referring to sales weighted delivery

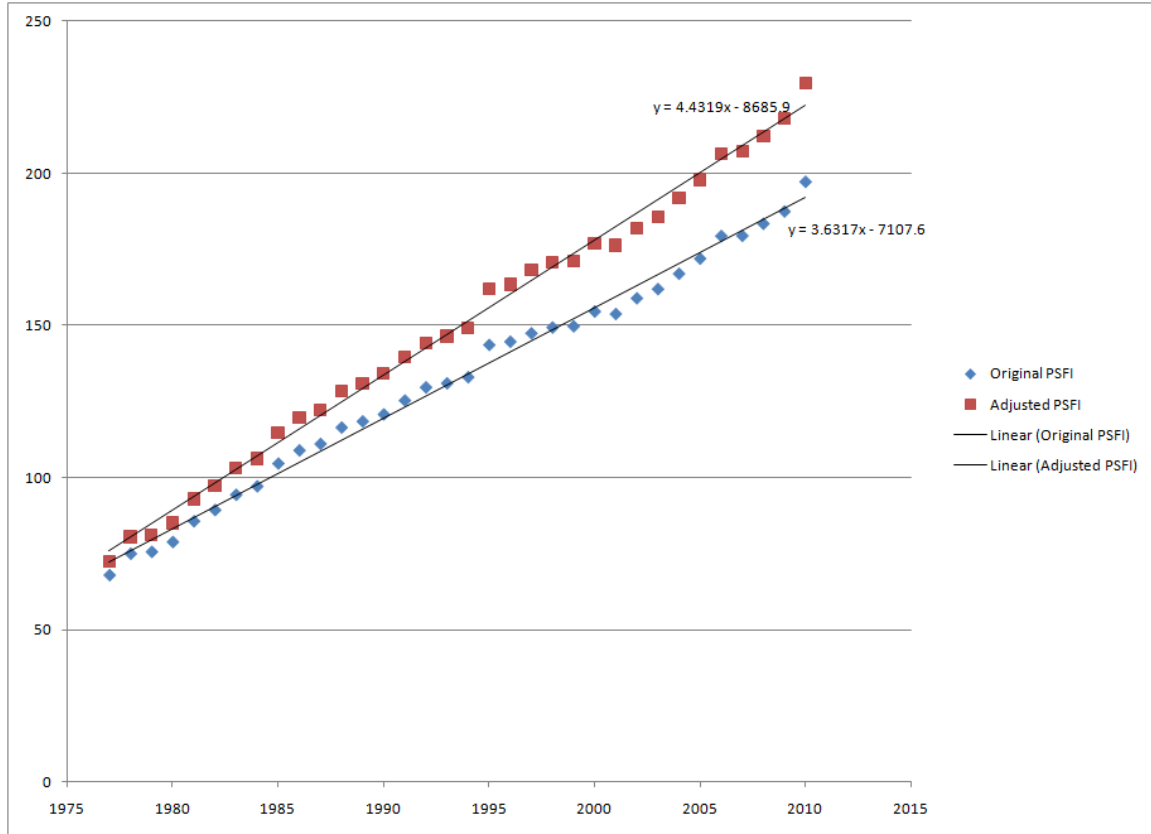


Figure 3-3: Traditional PSFI vs. Adjusted PSFI growth from 1977 - 2010.

of measurable vehicle amenities. However, both of these metrics are silent on the question of how different vehicle amenities can be traded off against one another.

[Cheah, 2010] uses a combination of techniques summarized in Table 3.1 to determine a "10-7" rule: that each ten percent in weight reduction results in a approximately a 7% reduction in fuel consumption for gasoline-powered midsize cars.

Alternatively [Knittel, 2009] uses a Cobb-Douglas model to determine that a ten percent decrease in weight would correlate to a 4.26% increase in fuel economy, or that a ten percent decrease in horsepower would result in a 2.57% increase in fuel economy.

Cheah, Knittel and MacKenzie have focused on tradeoffs among the conventional amenities size, performance and fuel economy. Literature to-date has not explored to what extent safety, emissions, and comfort/convenience features could be traded off against conventional attributes. A tradeoff analysis of features should extend beyond

Table 3.1: Fuel consumption (FC)-curb weight relationship for a current conventional gasoline midsize car, from [Cheah, 2010].

Approach		FC reduction per 10% mass reduction	FC reduction per 100 kg mass reduction
Literature Review		5.6-8.2%	0.36-0.58 L/100 km
Empirical data (MY2006-2008)		5.6%	0.36 L/100 km
Engineering (ADVISOR)	Simulation	6.9%	0.39 L/100 km

the exploration of vehicle mass as features also impose parasitic losses that reduce powertrain efficiency.

Chapter 4

Deployment Rates of Vehicle Technology

Chapter 4

Chapter 4 reviews literature on the technology adoption and, using data on deployment of features, identifies typical rates of deployment of specific features in the automotive fleet.

Each of the metrics discussed in the previous chapter: BMEP, ton*mpg, PSFI and $PSFI_{Adjusted}$ suggest that the growth in vehicle capability is strictly an evolutionary process resulting from marginal gains in performance in multiple areas. However, such marginal improvement in vehicle functionality can be better characterized as the product of the independent development of hundreds of individual technologies.

The deployment of technology is aptly characterized by a logistic curve (also S-Curve). One of the earliest uses of this functional form was used by Everett Rogers in describing the process of *Diffusion of Innovations*. An image of this process is shown in 4-1.¹

Per [Rogers, 2003] consumer adoption has depended primarily on five key factors:

¹In this chapter the terms diffusion and deployment are used interchangeably. These terms both describe the process by which innovations are brought to market, although the traditional term diffusion characterizes the process as consumer-driven, while deployment has connotations of being producer-driven.

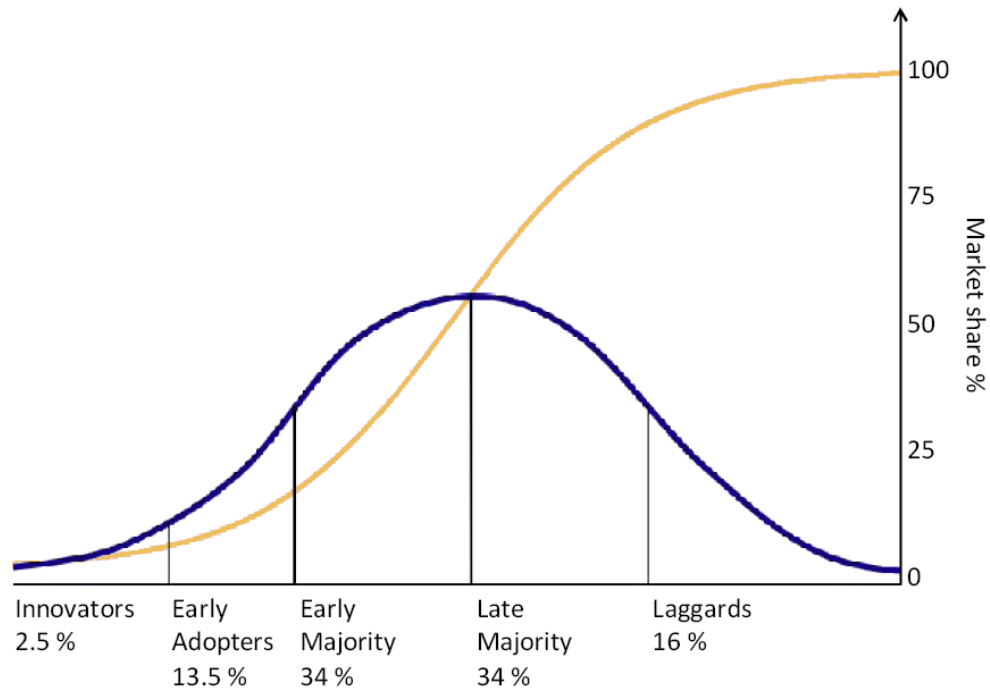


Figure 4-1: Functional form of the diffusion of innovations as envisioned by [Rogers, 2003]

Relative Advantage People will purchase an invention if they believe it will enhance their utility in some fashion.

Complexity The degree to which an innovation is perceived as relatively difficult to understand and use.

Compatibility The degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters.

Trialability The degree to which an innovation can be experimented with on a limited basis.

Observability The degree to which the results of an innovation are visible to others.

4.1 Common Models of Diffusion/Deployment

A wealth of literature has been published on the diffusion of innovations in various markets. One of the most commonly-cited of these, the Bass diffusion model, describes process of adoption as primarily the function of two effects: advertising and word-of-mouth.[Bass, 1969] Figure 4-2 shows a representation of this process using a System Dynamics model. The counterbalancing feedback loops of market saturation and word of mouth communication create the familiar S-shaped curve seen in diffusion models.

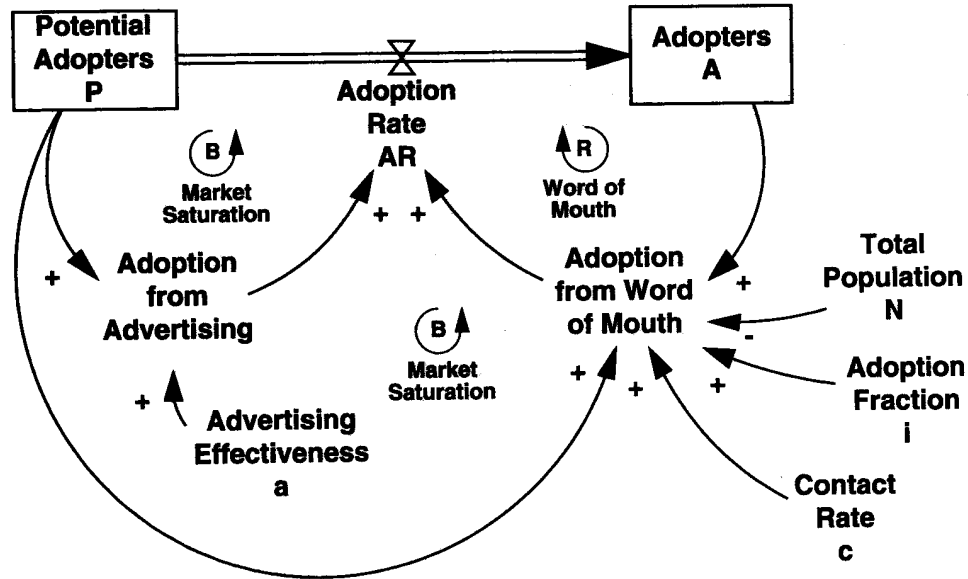


Figure 4-2: Functional form of the Bass diffusion model as envisioned by [Sterman, 2000]

4.2 Applying Regression

This chapter provides characterization of historical deployment rates of vehicle features intended to inform plausible deployment rates for future automotive technology.

For the purposes of this analysis, a least-squares regression with a logistic (S-

Curve) form has been applied to feature take rates gathered from the EPA Fuel Economy Trends report, Ward's Factory Installed data, and DOT report HS 809 834. The functional form of the regression used in these analysis is as follows:

$$TakeRate(t) = \frac{Limit}{1 + \alpha e^{-\beta t}}$$

Where,

Limit = Maximum Take of Features

t = time in years

α = regression parameter approximating lag

β = regression parameter approximating steepness

A complete list of features with charts of take rate data and applied regressions is provided in Appendices C - F.

4.3 Prior Work

[DeCicco, 2010] applies regression with a logistic form to feature data available from EPA for front-wheel drive, fuel injection, multivalve engines and VVT. The analysis proposes a logistic function and discusses both the steepness parameter of the adoption curve and also the number of years since the "first significant use" although it is unclear exactly what criteria have been used to establish this date. DeCicco also proposes a logistic function within the range of other powertrain technologies as a plausible deployment scenario for hybrid electric vehicles (HEVs) although the author notes that HEVs will compete with other technologies for incorporation into future vehicle fleets.

While [Kramer and Haigh, 2009] do not use the term "logistic function," the authors use descriptive language to identify phases of growth in the power generation sector that are remarkably similar to those seen in the automotive industry. Kramer and Haigh also discuss the importance of the developmental phase of new technol-

ogy, citing that it takes "time and industrial capacity"—not just capital investment—to deploy new technology.

[Nakicenovic, 1986] discusses the logistic form of the diffusion of technology in a variety of fields and identifies several examples of diffusion of automotive features. Nakicenovic also discusses differences among different types of vehicle features, a concept continued here with the differentiation among safety, powertrain, and comfort/convenience features. Nakicenovic cites examples of the time to reach 50% penetration of a new technology, a parameter referred to later in this chapter as "developmental lag time."

The work performed in this chapter updates the work performed by Nakicenovic with nearly 25 years of new data on a broader array of technologies. The larger quantity of data available also allows secondary regressions of fit characteristics.

4.4 Important Characteristics and Secondary Regression

In the form used here logistic regressions incorporate three primary characteristics: maximum take rate (or application), maximum growth rate (slope of the curve at its inflection point) and lag time, or delay in reaching the period of maximum growth as shown in Figure 4-3.

4.4.1 Maximum Take Rate

Unlike stand-alone products where a potential market needs to be identified, the sales of a particular feature of a passenger car cannot exceed sales of the car itself. As a result, the potential market is defined as the percentage of the new car fleet equipped with a given feature.

When examining historical maximum take rates, one soon encounters a problem: for most features where data is available, take rates have either already approached 100% or are projected to reach this saturation point. The reason for this is simple:

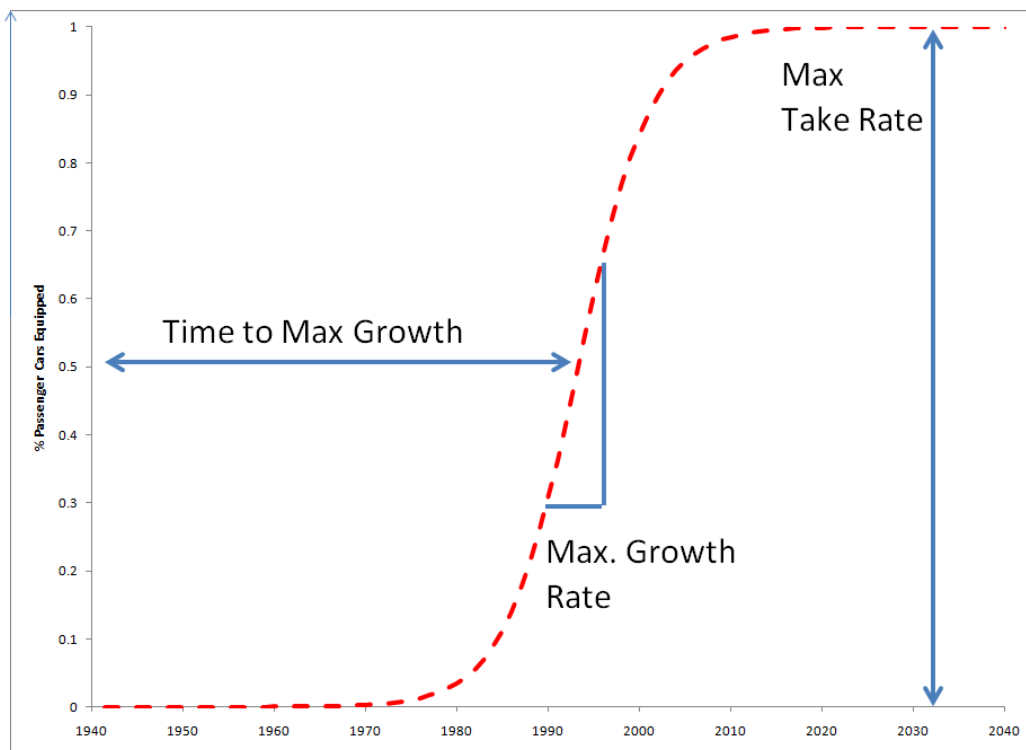


Figure 4-3: Important characteristics of a logistic function.

data is not closely tracked for technologies that are unsuccessful! At first blush this would seem to lead to a problem of selection bias, but a closer look is appropriate.

Examples of actual failed attempts to bring features to market in the automotive industry are not found in this data set.² When take rates for a given feature do fall it is generally the result of a technology supersession: eight-track players are replaced by cassette decks and CD players; traction control is replaced by stability control.

The question, then, seems to be one of boundary definition. Broadly defined, fuel injection has now saturated 100% of the new passenger car market. However, the growth in the use of fuel injection was in fact characterized by the successive uptake of mechanical fuel injection, throttle-body fuel injection, and port fuel injection as shown in Figure 4-4. Since the development of this figure Gasoline Direct Injection

²One potential exception to this conclusion are diesels in the US market. After reaching a peak of 6% of new passenger cars in 1981, diesels have fallen to less than a percent of recent new car sales. However, the argument can also be made that diesels were simply replaced by more preferable SI technology, thereby falling into the pattern of technology supersession discussed here.

(GDI) has seen large gains in use and may soon surpass other existing types of fuel injection.

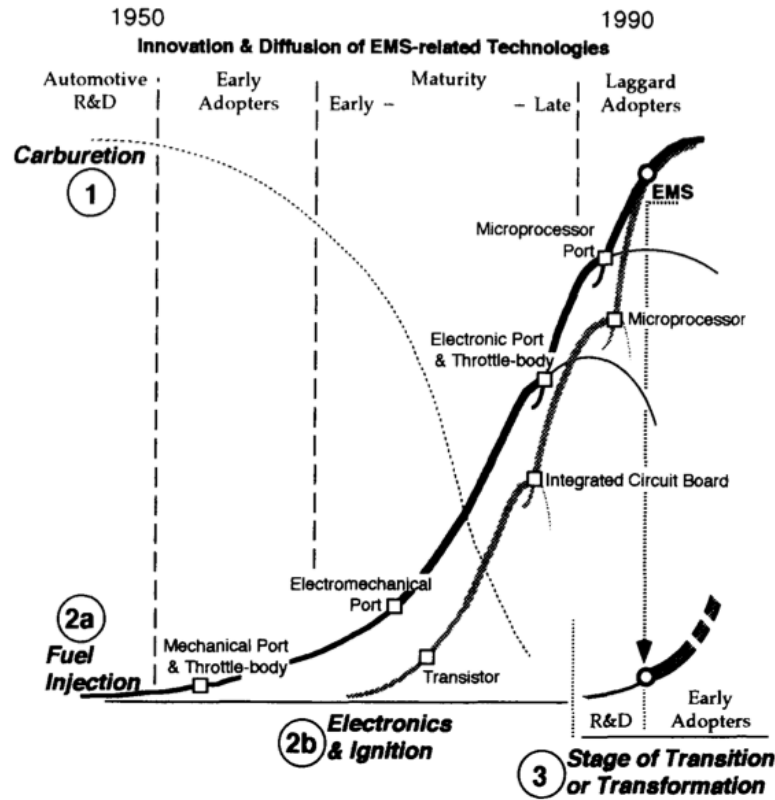


Figure 4-4: Technology supersession in fuel injection and engine management as envisioned by [Amey, 1995]

Technology supersession is not always entirely contained within the automotive domain. Two recent examples—mobile phones and navigation systems—also show evidence of technology supersession. In-car phones originally reached a high of 9% of new passenger cars sold in 2000, but in the past decade the paradigm of in-car electronics has been replaced by a model in which owners are presumed to buy a separate device. Take rates of in-car navigation systems are still increasing, but an increasing number of buyers use a stand alone portable navigation system or cell phone-based navigation application. Time will tell whether a market will continue to exist for factory-installed navigation systems with large screens and vehicle integration.

With this concept in mind, three common factors arise as indicators that a tech-

nology will not reach 100% take rate:

Limited Appeal (Example: Rear seat entertainment) Some features simply will not appeal to all buyers. Rear Seat DVD players, for example, are generally considered desirable by buyers with small children but are of very limited use to a large fraction of buyers.

Significant Tradeoffs (Examples: Automatic Transmission, Front-Wheel Drive) Some features or technologies inherently involve tradeoffs in other attributes. Automatic transmissions, for example, remove the feel of control that some buyers want. Front-wheel drive, while offering a benefit to fuel economy, requires the sacrifice of rear-wheel drive handling dynamics sought after by some buyers.

Competing Technology / Paradigm (Example: On-board Navigation) Some features and technologies compete with others for market share. On board navigation, for example, competes with mobile phones and portable navigation devices.

4.4.2 Maximum Growth Rate

The maximum rate at which the take rate of a technology grows is dependent on a variety of factors: consumer demand, producers' ability to bring the technology to market on its fleet and, in some cases, the influence of regulation.

DeCicco (2010), while using slightly different regressions than those in this analysis, points to the maximum growth rate (U_{Max}) of 17%/year for fuel injection in LDVs, 11%/year for front wheel drive in passenger cars. While DeCicco does not perform an explicit regression on other technologies, the proposed value of 7.6%/year a plausible adoption rate of HEVs is similar to those he shows for multivalve engines and VVT.³

³Non-linear least squares regression requires the use of starting values to begin optimization. Different starting values may result in the convergence on a variety of solutions, which may account for different regression values in the literature

However, as discussed in Chapter 2, each of these technologies has, to a varying extent, been driven by regulation. Figure 4-5 examines a histogram of the maximum growth rate of all features for which data is available. Figure 4-6 performs the same analysis but divides technologies into the functional categories of safety, powertrain, and comfort/convenience.

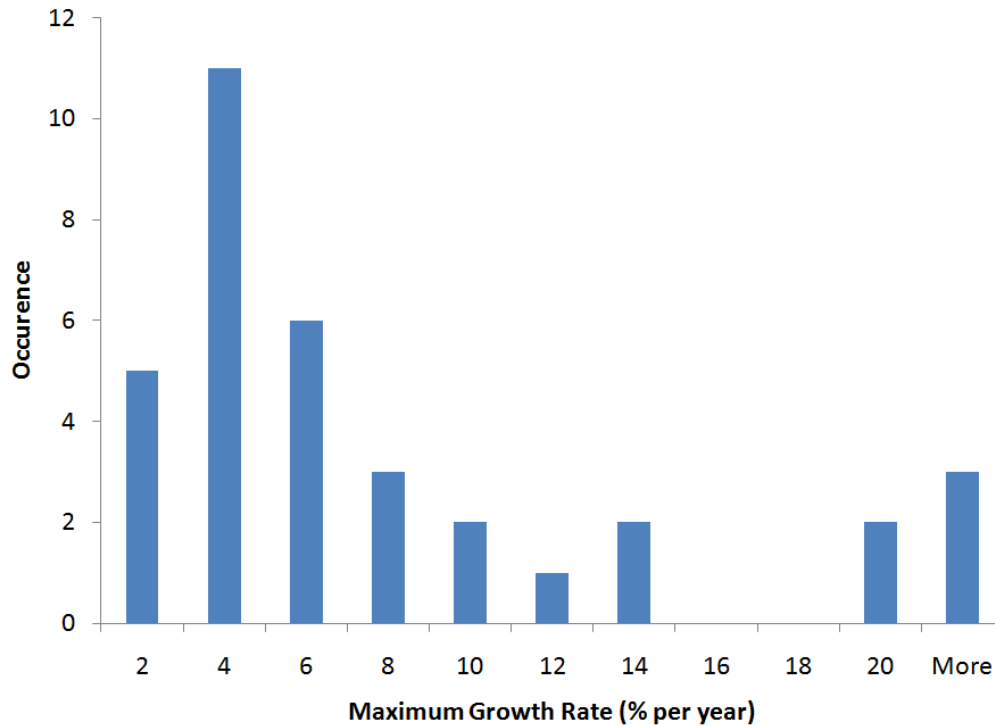


Figure 4-5: Histogram of maximum feature growth rates.

Peak annual growth rates range from 1% - 23.9%. Safety features see the fastest deployment among these categories, ranging from 4.5% per year to 23.9%. This maximum growth rate seems to confirm conventional wisdom, adopted in [NHTSA, 2010] and others, that an average five-year product development cycle is appropriate for modeling the automotive industry— even technologies with a clear life-saving benefit cannot be deployed much faster than 20% of the new vehicle fleet per year.

This histogram also seems to confirm the sentiment expressed by DeCicco, that the examples of technology growth in powertrain development commonly cited (FI, FWD, VVT, and Multivalve engines) exhibit "very rapid rates of change." In the

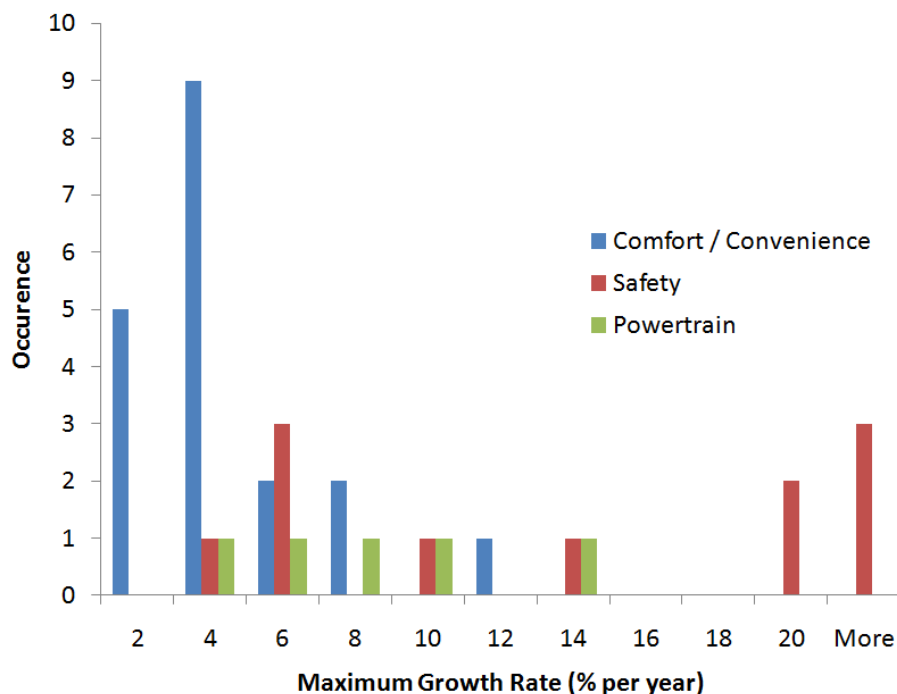


Figure 4-6: Histogram of maximum feature growth rate by category.

broader context of automotive features, yearly growth rates of less than 5% per year are more common.

The fastest growing of the comfort/convenience features, Satellite Radio, merits additional consideration. At 11% per year, Satellite radio is currently exhibiting very rapid growth in application for a feature where regulatory impact is not a consideration. Satellite radio has been the subject of a very aggressive marketing campaign in recent years. Since satellite radio is a subscription-based service, it represents a stream of residual revenue from the vehicle purchaser, typical shared between the satellite radio provider and vehicle manufacturer. As a result, OEMs have an incentive to push satellite radio to customers in the hopes that many of them will continue to subscribe. However, since the Wards data used in these regressions shows only the purchase of an option it is unknown how many of these customers actually activate the satellite radio service or are even aware of its installation.⁴

⁴Dealers may also receive a bonus for successfully selling options such as satellite radio. This compensation structure results in a push from every stakeholder to install satellite radio in a vehicle.

4.4.3 Developmental Lag Time

When a new technology or feature is brought to market in the automotive industry it is typically done in limited quantities and often on high-end flagship products. Fuel injection, for example, was first brought to market by Mercedes in 1954-55 on its 300SL race homologation vehicle. It was not until 1985, *three decades* later, that maximum growth in the mainstream automotive market was achieved.

This period of development and maturation seems to be not only the product of limited consumer demand, but also of an automotive manufacturing infrastructure building competence and confidence in a new concept.

The analysis shown here is a secondary regression comparing the inflection point from primary regressions to the date of the first production, street-going vehicle to use a technology. Since many features referenced here were developed before the earliest Wards data sets used, start dates have been identified using a variety of sources including Wikipedia, patent databases, and company advertising. As such, small discrepancies may exist in some start dates. A complete table of the values used for the charts shown below is available in Appendix G.

Figure 4-7 shows a regression of all features simultaneously, while Figure 4-8 shows independent secondary regressions by feature category. This analysis shows a dramatic, exponential decline in the developmental lag time of features deployed over the past century.

There are a variety of explanations for such a change in the automotive industry. It is theoretically possible that the marked decrease in developmental lag time of features is the product of more stringent consumer expectations resulting from more exposure to new products and features through new media, and a higher level of communication between consumers leading to greater Word of Mouth interaction between adopters and potential adopters.

However, improvements in supply side capabilities have likely played a strong role as well. [Clark and Fujimoto, 1991] and [Ellison et al., 1995] highlight that while U.S.

Many manufacturers also provide the service free of charge for a period of time, a way of increasing the trialability of the feature for potential customers.

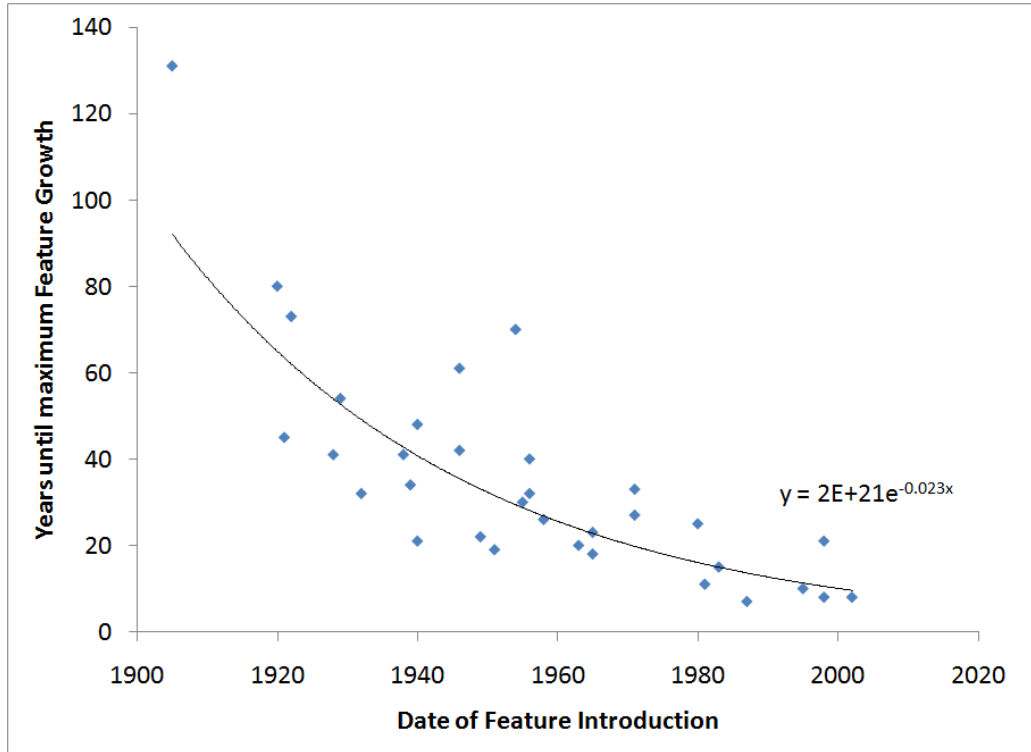


Figure 4-7: Historical phase-in time of all features.

and European automakers were at a significant disadvantage to Japanese producers in the 1970s and 1980s (Figure 4-9). However, by the mid-1990s they had reduced overall product lead time by nearly a year. The resultant increase in product changes allows a manufacturer to incorporate new features into the product mix more readily, while increasing competition pushes manufacturers to differentiate products by the incorporation of features with consumer appeal.

The structure of the automotive industry itself has also changed significantly over this same time period. Automakers are no longer vertically-integrated giants capable of receiving raw materials in one end of a plant and shipping cars out the other—the industry is now highly stratified and automakers are dependent on a pyramid of suppliers for components. [Ellison et al., 1995] highlight the increased role that suppliers play in the product development process. For U.S. suppliers, Ellison et al. (1995) find that supplier content in the product development process more than doubled from 15% to 33% from the 1980s to the 1990s. While Japanese supplier

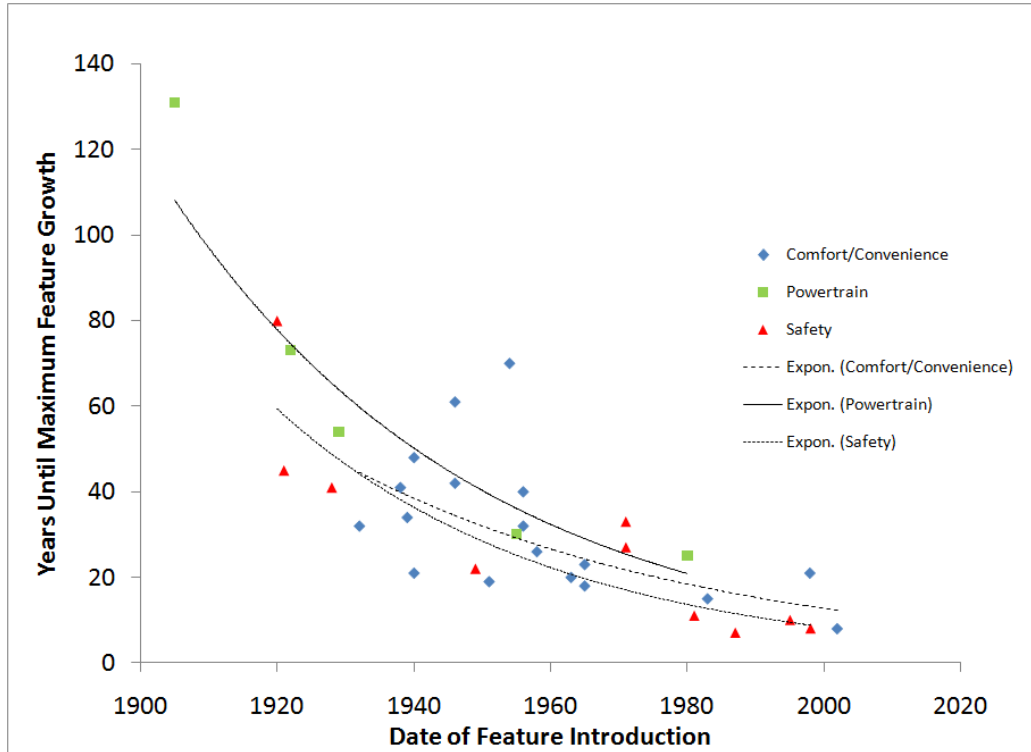


Figure 4-8: Historical decrease in phase-in time of features by category.

content decreased slightly over the same period, European supplier content increased. Increasing reliance on suppliers suggests that intellectual property is distributed more quickly as suppliers are free to market a new technology to a variety of manufacturers as customers.

However, despite these factors that dramatically different competitive landscape and decline, current developmental lag time still for new vehicle features remains on the order of approximately a decade, although this represents a dramatic decline since the 1950s.

4.5 Alternative Methodology: Z-Curves and Logistic Approximation

[Schafer et al., 2006] and [Bandivadekar, 2008] describes deployment of new automotive technology in three primary phases. The authors then project potential time

Pattern \ Region	United States	Europe	Japan
Average Number of Car Models	28	77	55
Number of New Car Models Developed	21	38	72
Average Major Model Change Frequency (years)	8.1	12.2	4.6

Figure 4-9: Product variety and model changes by region, adapter from [Clark and Fujimoto, 1991].

periods for these phases for a variety of technologies (shown in Figure 4-10). This section approximates the three phases used by Bandivadekar and Schafer et al. by extrapolating parameters identified by regression with a logistic form performed in the previous sections.

Table 4.1: Stages of deployment using parameters extracted from logistic regressions.

Implementation Stage	Vehicle Technology			
	Variable Valve Timing	Anti-lock brakes	Keyless Entry	Satellite Radio
Market Competitive Vehicle	17	15	9	4
Penetration across new vehicle production	15	25	12	8
Major fleet penetration	10+	10+	10+	10+
Total time required	42+	50+	31+	22+

In this analysis the periods of time for each phase of technology deployment are defined in the following manner. The "Penetration across new vehicle production" phase is defined as the maximum fit take rate from logistic regression divided by the maximum growth rate from the same regression. Conceptually this can be envisioned

Implementation Stage	Vehicle Technology				
	Gasoline Direct Injection Turbocharged	High Speed Diesel with Particulate Trap, NOx Catalyst	Gasoline Engine/ Battery-Motor Hybrid	Gasoline Engine/ Battery-Motor Plug-In Hybrid	Fuel Cell Hybrid with on board Hydrogen Storage
Market competitive vehicle	~ 2-3 years	~ 3 years	~ 3 years	~ 8-10 years	~ 12-15 years
Penetration across new vehicle production	~ 10 years	~ 15 years	~ 15 years	~ 15 years	~ 20-25 years
Major fleet penetration	~ 10 years	~ 10 -15 years	~ 10 -15 years	~ 15 years	~ 20 years
Total time required	~ 20 years	~ 25 years	25 -30 years	~ 30-35 years	~ 50 years

Figure 4-10: Stages of deployment of new vehicle technology. Image from [Bandivadekar, 2008], adapter from [Schafer et al., 2006]

as the line of maximum slope being extended until it intersects the x-axis and the maximum take rate (generally 100%).

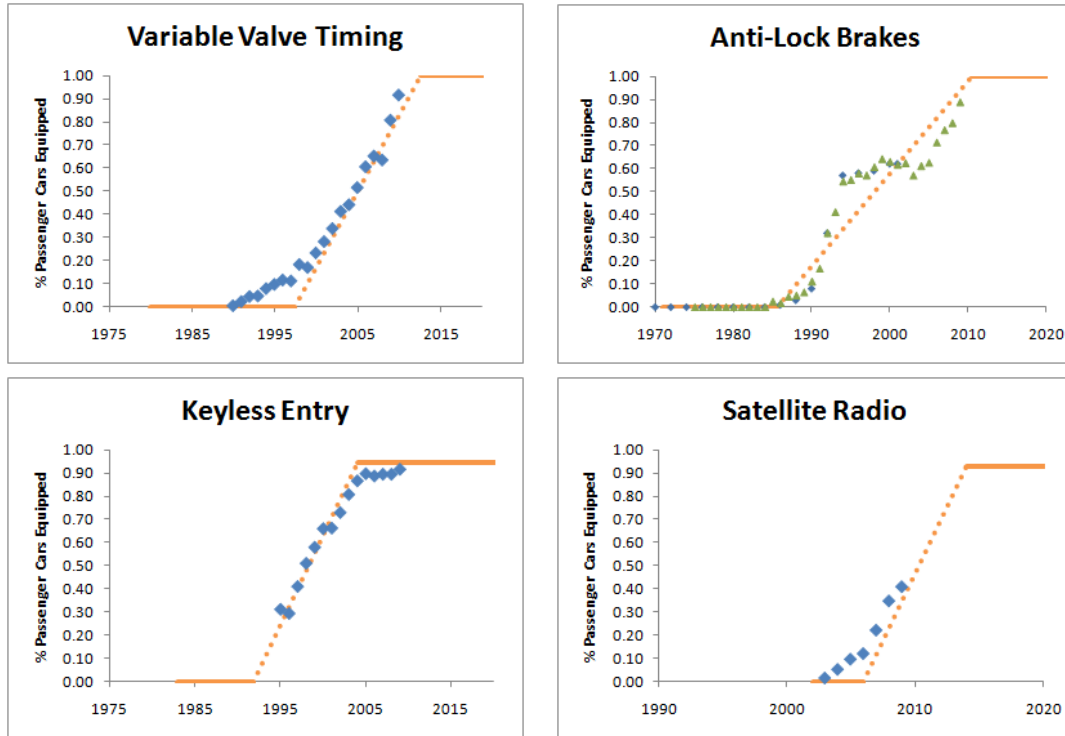
The "Market Competitive Vehicle" phase is defined here as time between the first production application and the x-axis intercept of maximum growth, or: $Date_{MaxGrowth} - Date_{Introduction} - (GrowthRate_{Max}/2 * TakeRate_{Max})$.

The "Major Fleet Penetration" phase is not addressed here as it is generally the product of fleet turnover rates. The "10+ years" value is used in all cases.

Table 4.1 shows the results of applying such parameters to four examples of technologies with varying function, complexity and timing. This analysis confirms that for a variety of historical examples the time periods Schafer identifies are plausible.

Z curve fit parameters for all relevant time series feature data is plotted in Appendix G. The last column, ratio, represents a ratio of the time spent in the development phase over the time spent in the deployment phase. Values greater than 1 indicate that more time is spent in development than deployment, while values less than one indicate that deployment takes longer than development.

Table 4.2: Z-curve: Phases of deployment and actual percentages of new vehicles sold with each technology for the four examples used in the previous table.



4.6 Differences Among Manufacturers

The analyses performed in the previous sections show trends in the new passenger car fleet as a whole. However, the automotive market is composed of a range of independent companies from large, full-line producers to boutique operations or those that compete only in a few segments. A fleet-wide analysis does not show differences between such varied producers.

4.6.1 Manufacturer-Specific Action and Fleet Impact

Figures 4-11, 4-12, and 4-13 show sales-weighted deployment of three key power-train technologies in the U.S. passenger car fleet overlaid with the start and finish of implementation by ten major automotive manufacturers based on data drawn primarily from the EPA fuel economy trends database. The manufacturers include three U.S., three European, and four Japanese auto manufacturers.

The manufacturer-specific bars start with the release of the first model including the technology and end with the phase-out of the last model *not* including the technology. The bars thereby represent the transitional period for each manufacturer with respect to the technology. In each case the bars have been ordered by the first use of the technology, with the manufacturers at the lower end of the chart beginning earliest.

Several key factors surface upon examination of technology deployment on a manufacturer-by-manufacturer level.⁵

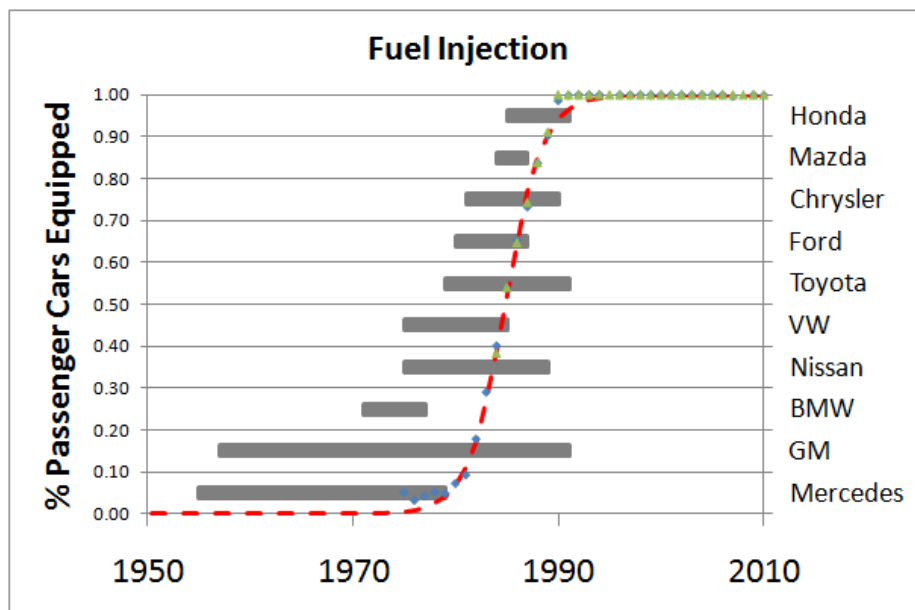


Figure 4-11: Differences among automotive manufacturers in phase-in of fuel injection.

Individual Producers Are Faster Than the Market

While fleet-wide deployment may take decades, individual manufacturers are capable of deploying technology much faster. Mazda deployed Fuel Injection, VVT and Multivalve engines across its entire product portfolio in three, four, and eight years respectively.

This is a special case as Mazda has traditionally been an OEM with a limited

⁵Small distinctions arise in this analysis. Chrysler began experimenting with fuel injection around the same time as GM and in fact sold a small number of vehicles equipped with the Bendix "electrojector" system. However, because the system was installed post-production and was purportedly installed on fewer than one hundred vehicles it is not counted as a start date here.

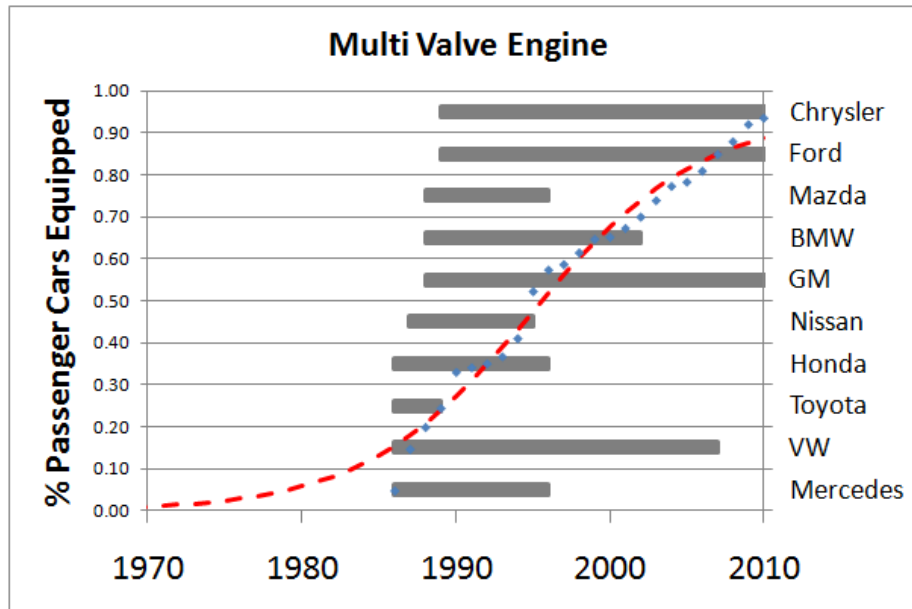


Figure 4-12: Differences among automotive manufacturers in phase-in of multivalve engines.

product portfolio, but other manufacturers have also shown the ability to move quickly when necessary.

First mover advantage? An automotive producer that is first to market with a new technology is *not necessarily* the first to roll out the technology to its entire fleet. GM, second only to Mercedes in launching fuel injection, was among the last to discontinue use of carburetors while Mazda, despite a late start, was able to completely deploy fuel injection across its vehicle portfolio in only three years. These small-scale deployments are, however, needed to build experience with a new technology necessary for a larger rollout.

Fleet Impact One or two manufacturers experimenting with a new technology will not make a meaningful impact in fleet-wide numbers. Fuel injection had been in production on street-going vehicles for more than two decades before total fleet penetration exceeded 10%. Similarly, Variable Valve Timing only exceeded 10% fleet-wide deployment when six major manufacturers had begun to use the technology on at least one vehicle.

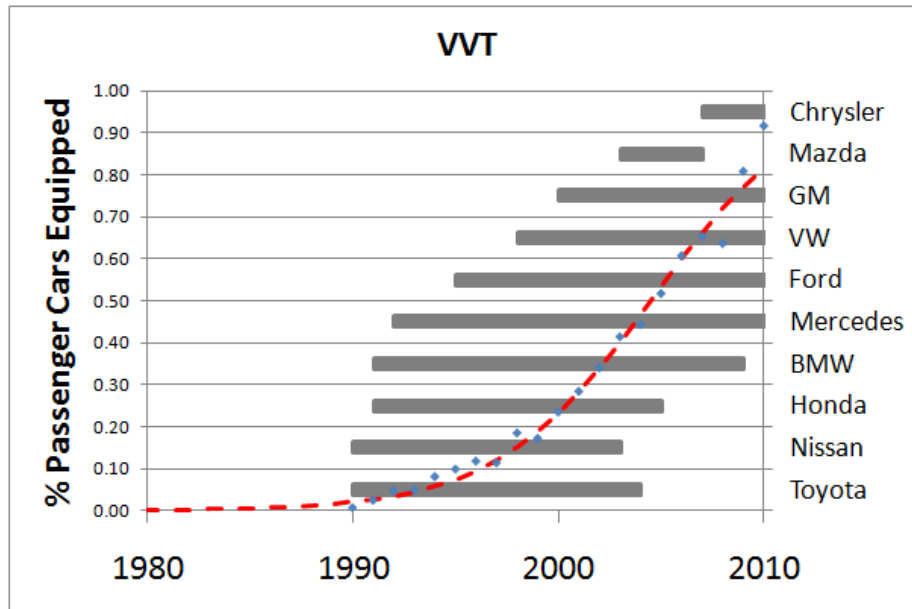


Figure 4-13: Differences among automotive manufacturers in phase-in of variable valve timing.

4.6.2 Strategies Within Manufacturers

Examining one step closer (at the individual model level) we can see that companies sometimes find it advantageous to buy new technology from a competitor to gain experience quickly. Ford's first multivalve engine was found in the Taurus SHO, a high-performance sedan with an engine built by Yamaha. Chrysler's first multivalve engine was in variants of the Dodge Colt, a product of the Diamond Star Motors (DSM) joint venture with Mitsubishi.

A trend that appears nearly universal is that automakers generally launch new technology on high-end luxury or performance products first: Toyota's first fuel injected product was the Celica Supra; Honda's first car with VVT was the Acura NSX; Nissan's first car with VVT was the Infiniti Q45 and Toyota's first car with Direct Injection was the Lexus IS F. Many of these technologies descend from racing vehicles and this seems to be the literal embodiment of the old adage "race on Sunday, sell on Monday." A number of examples of this are discussed in the following paragraphs.

Through 1978, Toyota's entire fleet was carbureted. In 1979, Toyota equipped the Celica Supra, a performance car, with fuel injection. In 1979 Toyota added FI to the

Cressida, its luxury car. These two models continued until 1983, when the Starlet, the Camry and certain Celica models with FI. Toyota continued to migrate its vehicle portfolio over to FI through the subsequent years; the majority of Corolla and Tercel models migrated to FI in 1990, although a few variants of the Tercel and Corolla were not changed until 1991, at which point Toyota's fleet was entirely fuel injected. The total time of transition from carburetion to electronic fuel injection was eleven years. While the data in the Trends Report is not sales weighted, the transition began with more expensive, relatively low volume vehicles and finished with the inexpensive cars in Toyota's portfolio.

BMW's first cars with four valves per cylinder were released in 1988. These models are listed in the Trends Report database as the 3, 6, and 7 Series, although the horsepower values in the database indicate that these were limited production variants using the Motorsport-developed high-output engines. Only these models were produced with four valves per cylinder for three years. BMW rolled out multi-valve engines across much of its product portfolio very quickly from 1991-1994 and by 1995 only BMW's V12 engine used two valves, but production of this engine continued through 2001. From 2002 - On all BMW's vehicles have used multivalve engines. The total time of transition from two-valve to multi-valve engines was thirteen years, although the majority of the change in the portfolio took place during four years. The transition began with low-volume, high-performance vehicles.

4.7 Supply Side Constraints on Deployment

[Bandivadekar, 2008] calls attention to the importance of supply side constraints in determining the speed with which new technology can be brought in to the new automotive fleet. The four factors listed by Bandivadekar are paraphrased below.

Development lead times and availability across product platforms Time needed for development and integration of components in a vehicle platform.

Capital investment required Time and capital required to retool a production

facility.

Supply of critical systems/components Possible shortages in production of components for new technologies.

Capacity utilization Need to balance shifting product demand with maintaining production volumes.

Table 4.3: Supply side constraints by product development role.

Concept Development	Integration, Testing	Production	Market Adoption	Market Support
(Researchers, Suppliers)	(Automotive OEM)	(OEM, Suppliers)	(Consumers, Regulators)	(OEMs, Suppliers, Dealers)
IP Boundaries	Engineering Expertise	Retooling Capital	Attribute Desirability	Warranty, Recall costs
Design Capital	Platform Demands	Redesign schedule	Price	Repairability
Component Costs	Durability Testing	Material Costs	Regulatory Compliance	Dealer Training
	Safety Testing	Capacity Constraints		

Table 4.3 expands upon the constraints identified by Bandivadekar and classifies them by the role and responsible party with which the task is most closely associated.⁶ The roles, as described here, reflect the automotive product development environment as it exists today; thirty years ago these constraints were more wholly within the domain of the automotive OEM.

4.8 Impact of Regulation

As discussed in Chapter 2, the impact of regulations on automotive technologies and features is often unclear. Adoption of applicable technology is often well under way before a regulation requiring it is made law, and many features offer marketable benefits other than mere regulatory compliance. A list of such features where regulation

⁶While this table is situated in a discussion of supply constraints, factors within the fourth column are market-driven and not strictly within the domain of the supply side.

has impacted deployment with relevant legislation and dates is shown in Table 4.4, and a chart of maximum growth rates for regulated vs. unregulated features is shown in Figure 4-14.

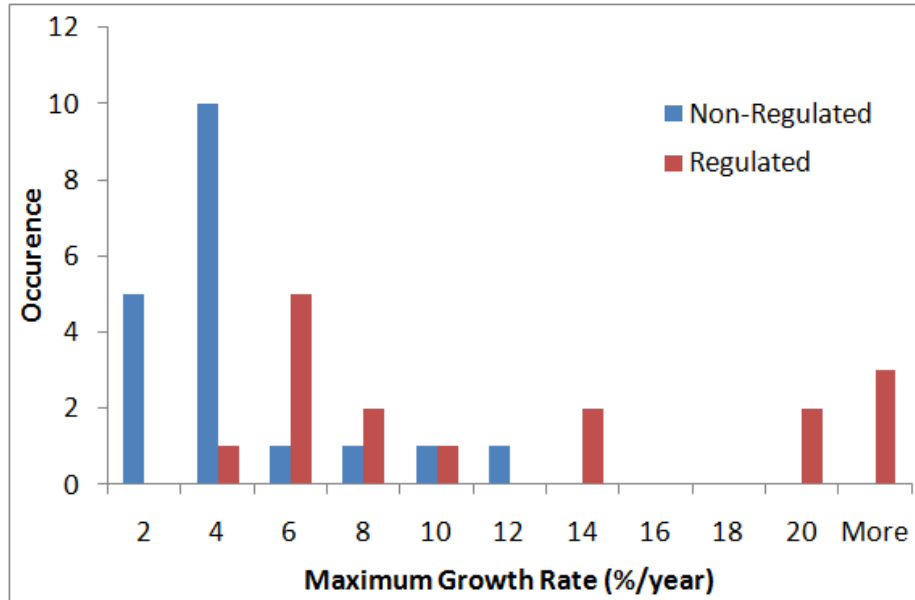


Figure 4-14: Differences in maximum growth rates between regulated and non-regulated features.

Where possible the "Date Issued" in Table 4.4 is the year of governing legislation or the Notice of Proposed Rulemaking for the relevant standard, identified by the date added to the Federal Register, with additional clarification from [DOT, 2004a] and [DOT, 2004b]. This date is generally the first public notice of an agency's intent to issue a rule.

On its face this date is a trigger for an automaker to begin preparing for compliance but these dates are imprecise for two reasons: first, automakers may anticipate that a rule will be delayed or abandoned during the Notice and Comment process and postpone compliance activity until a final rule. Alternatively, automakers may become aware of pending regulations during informal communication with regulatory agencies and begin compliance activity in advance of an official NPRM.

If deployment of a feature is high prior to regulation, a governmental standard will only force a feature to be applied to laggard vehicles in the fleet at a minor cost.

Table 4.4: Regulations applicable to features analyzed in this chapter. Standards with an asterisk are flexible standards that could be achieved via this feature or other means; regulations without an asterisk are strict requirements.

Feature	Applicable Regulation	Date Issued	Effective Date	New Passenger cars equipped at Issue Date
Intermittent Wiper/Washers	FMVSS 104	1966	1968	unknown
Rear window defogger	FMVSS 103	1966	1968	unknown
Front Wheel Drive	CAFE*	1975	1978 - Present	7%
Fuel Injection	Clean Air Act Amendments*	1970 - 1990	1975 - 1994	5%(1970)
	CAFE*	1975	1978 - Present	
Multivalve	Clean Air Act Tier II*	1999	2004 - 2009	65%
VVT	Clean Air Act Tier II*	1999	2004 - 2009	17%
Dual Master Cylinders	FMVSS 105	1966	1968	~69%
Front Disc Brakes	FMVSS 105a*	1970	1976	41%
Power Brakes	FMVSS 105*	1975	1976	~74%
Anti-Lock Brakes	FMVSS 126*	2005	2009 - 2012	63%
Driver Front Airbag	FMVSS 208I*	1984 (final)	1986 - 1995	<2%
Dual Front Airbags	FMVSS 208	1993 (final)	1996 - 1997	14%
Side Impact Beams	FMVSS 214	1968	1973	<17%
Curtain Airbags	FMVSS 208	2011	2013-2018	>91%
Traction / Stability Control	FMVSS 126	2005	2009 - 2012	14%
Alarm / Immobilizer	Motor Vehicle Theft Prevention Act*	1984	1984	<9%

Alternatively, if deployment of a feature is low prior to regulation, a governmental standard requires the entire automotive industry to adapt its fleet in compliance at a potentially high cost. As shown in Table 4.4, deployment rates prior to regulation have ranged from less than two percent to more than 90% of the passenger car fleet.

Figure 4-15 plots the maximum yearly growth rate of deployment on new passenger cars vs. the percent of vehicles equipped with a feature at the time the relevant regulation was announced. No clear trend linking maximum growth rate to the level of prior deployment can be shown. If regulatory agencies were engaging in aggressive forcing of technology, one would expect that when a regulation is announced early in the development process (when take rates are low) that maximum growth rates would be higher than when a regulation occurs after most vehicles are already equipped with a feature. Figure 4-15 shows that this is not necessarily the case, and that the interaction between regulation and deployment is more complex.

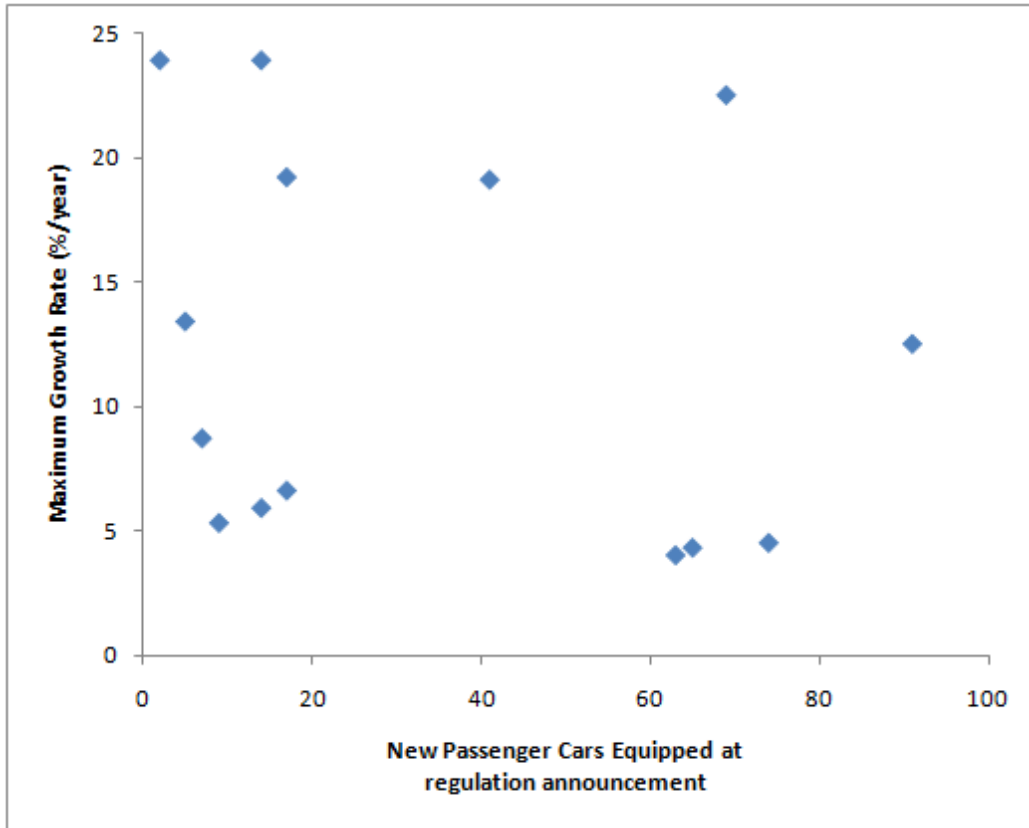


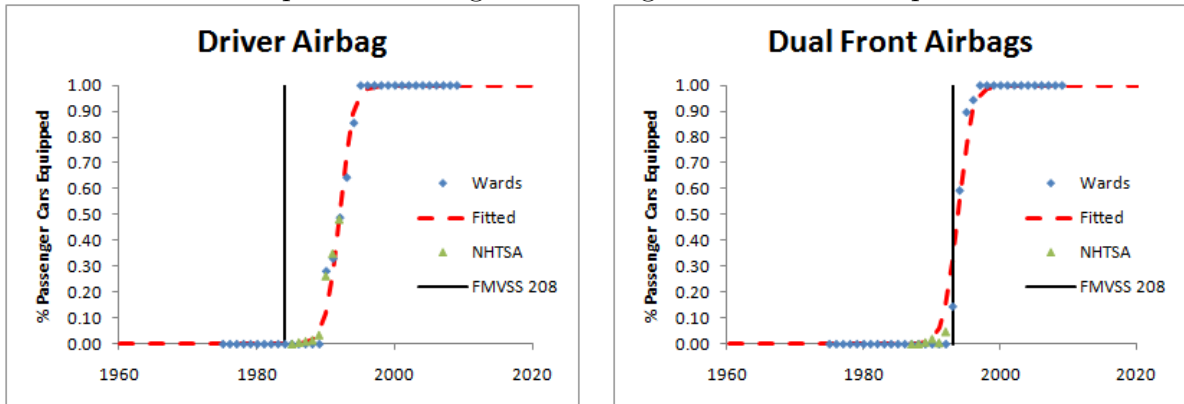
Figure 4-15: Maximum growth rate vs. number of passenger cars equipped at time regulation is announced.

A few brief examples of how legislation has interacted with deployment of vehicle features are discussed in the following sections.

4.8.1 Frontal Air Bags

Driver frontal airbags, which were installed on less than 2% of passenger cars in 1984, became a method of compliance with FMVSS 208 standards announced in 1984 (final rule) requiring passive safety devices. However, FMVSS 208 also initially permitted automatic seat belts to achieve compliance and it was not until 1993 that a final rule requiring both passenger and driver side airbags on 100% of passenger cars was issued.[DOT, 2004a] Impact of these regulations is shown in Table 4.5.

Table 4.5: Adoption of airbags and timing of FMVSS 208 requirements



4.8.2 Anti-lock Brakes

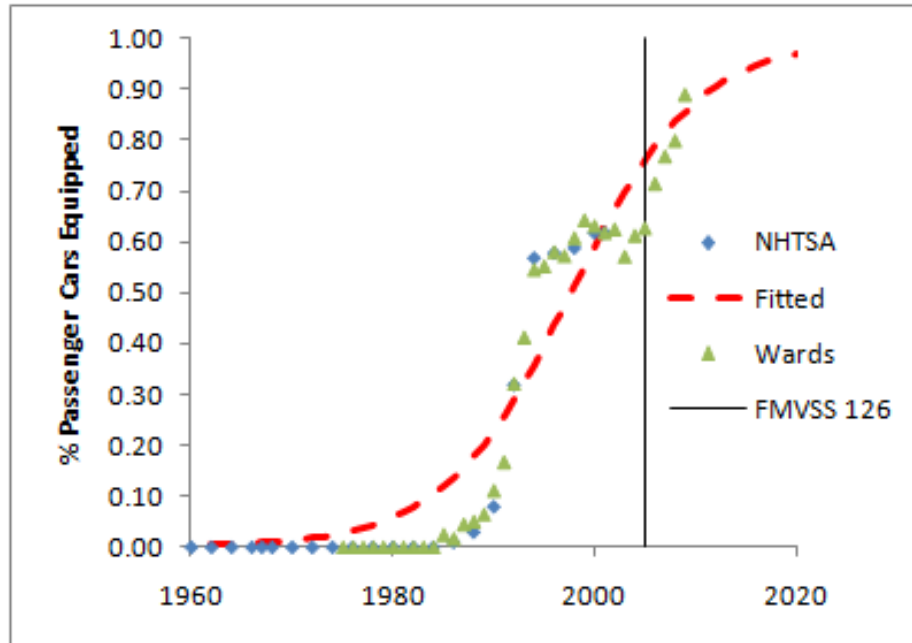


Figure 4-16: Adoption of ABS and timing of FMVSS 126 NPRM.

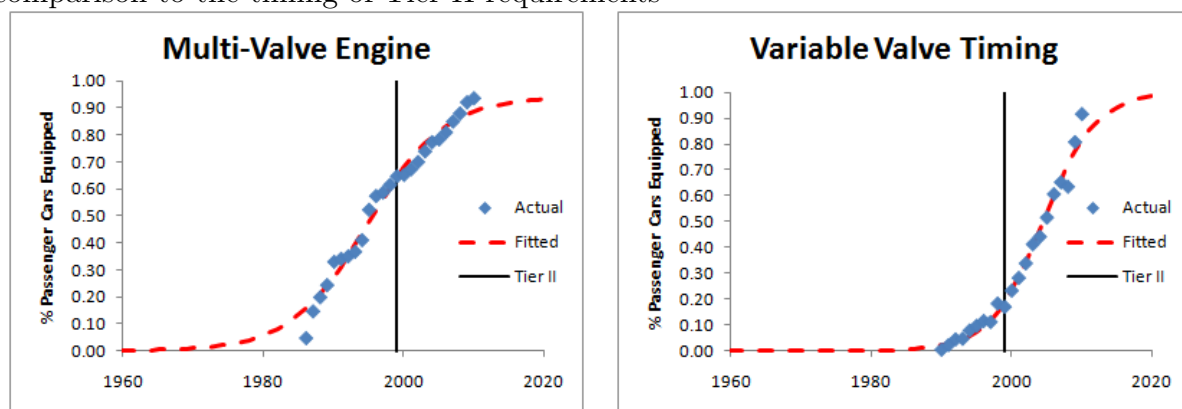
In the case of Anti-lock Brakes(ABS), regulatory impact is clear despite widespread adoption before regulation. Anti-lock brakes, first made available in the early 1970s, were equipped on approximately 63% of the passenger car fleet in 2005. Figure 4-16 indicates that adoption of ABS was leveling off and predicted to stabilize at approximately 65%.

In 2005 NHTSA announced FMVSS 126, which required all vehicles to be equipped with Electronic Stability Control (ESC) starting in 2012 (phase-in beginning in 2009). While it is theoretically possible to implement ESC without the use of ABS, the unusual double sigmoid characteristic of Figure 4-16 suggests that automakers are treating FMVSS 126 as a *de facto* requirement for ABS. As a result, application of ABS has again begun to increase and will reach 100% by 2012. Since this regulation apparently alters the saturation point of ABS and not particularly the growth rate, this effect is not captured by Figure 4-15.

4.8.3 Multiple valves and Variable Valve Timing

According to [EPA, 1999], multiple valves per cylinder and variable valve timing are both technologies that were important in reducing emissions to the levels required by EPA Tier II requirements. These requirements were announced in 1999 and phased in from 2004 - 2009.

Table 4.6: Adoption of multiple valves per cylinder and variable valve timing in comparison to the timing of Tier II requirements



By 1999, 65% of passenger cars were already equipped with multiple valves per cylinder, but only 17% used variable valve timing. Some manufacturers, including Mazda and Chrysler, had not marketed any vehicles with variable valve timing by 1999.

Some evidence of the accelerative effect of Tier II requirements on the implementation of variable valve timing can be seen during the phase in period: from 2004

- 2009 variable valve timing grew nearly ten percent per year with an actual peak growth rate from 2008 - 2009 of 17%, far in excess of the 7% per year maximum growth rate predicted by the fit logistic curve.

4.9 Conclusions

The objective of this chapter has been to characterize historical deployment rates of technologies and use these characterizations to make useful predictions about the plausible future deployment rates.

All features require significant developmental time before they can be deployed in the vehicle fleet at significant rates. This developmental period has been reduced drastically in the past sixty years, from more than 50 years of developmental time prior to 1950 to approximately ten years for recently developed features.

Maximum annual growth in feature penetration of 6% per year or less is far more common than growth rates of 10 - 24% per year. Features that improve vehicle safety will generally be adopted in new cars faster than either powertrain or comfort/convenience features, which generally see maximum growth rates of under 4% annually.

Future automotive features could be reasonably expected to follow a similar pattern: small-scale deployment for approximately five years leading to exponential growth and an inflection point ten or more years after first application.

This analysis also highlights the extent to which regulation has played a part in technology deployment in the automotive industry. The majority of features with peak growth rates in excess of 6% per year have been impacted by some form of regulatory intervention— either emissions standards, as is the case for most powertrain innovations, or NHTSA safety standards in the case of airbag and brake systems.

However, it is unclear whether regulation actually *causes* deployment to occur more rapidly, or whether technologies for which regulation is enacted are also those where market and supply-side factors lead to rapid growth in adoption rates. Side and curtain airbags represent counterexamples to the idea of regulatory forcing, with

maximum growth rates of 9% and 12.5%, respectively, prior to a regulatory requirement.

This analysis does not explore performance metrics such as the Insurance Institute for Highway Safety (IIHS) or NHTSA New Car Assessment Program (NCAP) crash tests. Vehicle manufacturers may add additional safety equipment to improve performance in such tests that is not strictly required by regulation.

Chapter 5

Findings, Applications and Conclusions

Chapter 5

Chapter 5 highlights conclusions that can be drawn from analysis of vehicle mass and technology deployment trends and ways that these findings could be applied to existing models. This chapter also notes limitations to this analysis and potential extensions for further work.

This thesis has focused on two key themes: the role features have played in the development of passenger cars, and characterization of the deployment of new features and technology in the passenger car fleet. The conclusions from each of these areas are discussed below.

5.1 Vehicle Mass Findings

The average mass of U.S. passenger cars dropped from 1845 kg in 1975 to a low of 1378 kg in 1987. Since then, mass has climbed steadily, reaching 1591 kg in 2010. However, absent developments in safety, emissions and comfort/convenience the average passenger car would have been approximately 1735 kg in 1975, a low of 1254 kg in 1987 and 1368 kg in 2010, a growth rate of just under 5 kg per year *without*

vehicle features.

Despite the incorporating of increasing levels of technology, vehicle mass continues to grow, and this growth strongly parallels increased applications of vehicle features. The analysis of optional and required features indicates that both the absolute mass contribution and the percentage of passenger car mass devoted to features are increasing, from a total of 109 kg (5.9%) in 1975 to approximately 223 kg (14%) in 2010 on a sales-weighted average basis. Optional features that enhance the comfort and utility of passenger cars are the largest mass contributor at 136 kg in vehicle mass.

Extrapolation of current trends indicates that features would contribute a total of 386 kg to the average vehicle mass in 2050, suggesting that if other vehicle attributes are unchanged from 2010, average vehicle mass could reach 1977 kg.

5.2 Feature Deployment Findings

The deployment of technology in the automotive industry is not simply the result of consumer demands but also the product regulatory influence and infrastructure constraints that prevent the rapid diffusion of innovation possible in other consumer industries. The timescales for the development of a new feature, from first application to maximum growth, are measured in decades. However, this developmental time has decreased exponentially and modern features achieve maximum growth rates in approximately ten years.

Features that enhance the safety of passenger cars exhibit more rapid maximum growth, on average, than either powertrain or optional comfort / convenience features, but growth in excess of 15% per year is rare and has only been possible for features with a life-saving benefit. For powertrain features, maximum growth of 6 - 14% is more typical. The majority comfort / convenience features do not exceed growth rates of 6% annually, and in only one case have exceeded 8% per year.

The impact of regulations is difficult to ascertain. While features affected by a regulatory requirements do generally have higher growth rates than unregulated features, an expected correlation between early regulation and higher growth rates is

absent. Specific examples indicate that regulations affect maximum growth rate and maximum take rate in differing ways.

Individual manufacturers may deploy technologies much more quickly than industry average time scales, but penetration of a feature or technology in the new car fleet is typically not significant until most major automakers have begun deploying the technology. Perhaps contrary to intuition, manufacturers that are first to market with a specific feature may not be those that are able to apply fully to their fleet first.

High performance vehicles will continue to play a significant role as platforms for small-scale deployments of technology that lead the mass market. The generally higher purchase price of these vehicles allows application of technology that could not be incorporated in lower-priced vehicles.

5.3 Applications for Policy and Vehicle Fleet Models

An immediate application of these feature and deployment guidelines is to inform vehicle fleet models used to predict future GHG emissions and fuel consumption.

Many fleet models operate with a presumption of emissions and fuel consumption *reduction* due to the increased application of technology, and use "no change" or Business As Usual (BAU) scenarios to describe a worst-case where current vehicle characteristics and focus on performance continue unabated. Such models should anticipate the continued growth in mass allocated to vehicle features. As a result, either vehicle mass will continue to grow or increasingly aggressive weight-saving techniques will be needed just to maintain current vehicle mass.

Other models, such as the Volpe Model [NHTSA, 2010] used to support CAFE regulations, attempt to identify plausible deployment rates of technology to help set fuel economy regulations at an economically optimal level. In this model NHTSA has incorporated an assumption that vehicles are, on average, redesigned every five years. In Chapter 4, few features exceed growth rates of 20% per year. This indicates that

NHTSA’s assumption of a five-year product redesign cycle is a reasonable one.

The Volpe Model uses a combination of ”phase-in caps” and manufacturer redesign cycles to estimate reasonable limits on technology deployment and as a proxy for supply-side constraints discussed in Chapter 4. Examples of these phase-in caps are shown in Table 5.1. Due to the other constraints incorporated in the Volpe model, actual application of these technologies applied by the model are lower, as shown in Table 5.2.

Table 5.1: A sample of specific technology phase-in caps from current CAFE legislation, referenced from Table V-12 in [NHTSA, 2010]

Technology	2012	2013	2014	2015	2016
Engine Friction Reduction	100%	100%	100%	100%	100%
Stoichiometric Gasoline Direct Injection	85%	85%	85%	85%	85%
Combustion Restart	0%	0%	85%	85%	85%
Turbocharging and Downsizing	85%	85%	85%	85%	85%
Dual Clutch or Automated Manual Transmission	85%	100%	100%	100%	100%
Electric Power Steering	85%	85%	85%	100%	100%
Power Split Hybrid	3%	6%	9%	12%	15%

Table 5.2: A sample of specific technology application levels output from the Volpe model to support 2016 CAFE regulation, referenced from Table V-48 in [NHTSA, 2010]

Technology	2012	2013	2014	2015	2016
Engine Friction Reduction	28%	50%	55%	58%	66%
Stoichiometric Gasoline Direct Injection	18%	26%	31%	35%	38%
Combustion Restart	0%	0%	2%	5%	11%
Turbocharging and Downsizing	13%	20%	21%	25%	27%
Dual Clutch or Automated Manual Transmission	24%	38%	48%	61%	69%
Electric Power Steering	40%	54%	57%	59%	72%
Power Split Hybrid	5%	5%	6%	5%	5%

Phase-in caps in the 2016 CAFE rule are immediately set to 85 - 100% for a majority of powertrain technologies. Hybrids, diesels, and a few advanced combustion technologies are initially set lower. However, when constrained by other model factors these rates fall. Most of the examples shown in Table 5.2 fall within the ranges of maximum historical growth rates identified in Chapter 4 for powertrain features. Dual

Clutch Transmissions and Electric Power Steering, for example, exhibit a maximum modeled growth rate of 14% per year. This rapid application of technology is on par with the most rapid rates of non-safety technology seen in historical data analyzed in this thesis.

For other features, technology readiness is an important consideration. The ten-year developmental lag times identified in this analysis have been defined as the period from the first *production* application of a technology, and experimental laboratory development time has not been counted. While most of the powertrain technologies contained in the 2016 FRIA are already in production, NHTSA incorporates a few technologies (i.e. combustion restart) that have not yet been incorporated into a production vehicle, and additional pre-production development time needed for such technologies would be in addition to the development times discussed here.

Technical readiness is a clear concept when applied to a specific technology, i.e. Gasoline Direct Injection. However, some technologies identified in 2016 CAFE documentation are not clearly defined. "Engine Friction Reduction," Aero Drag Reduction," and "Low Friction Lubrication" are not achieved through a single technology or feature and the baseline friction or drag values will be different for each manufacturer. As a result, it is difficult to speculate about whether the underlying design changes and technologies necessary to achieve these efficiency improvements are, in fact, ready.

Previous CAFE regulations have generally set fuel economy targets only 5-6 years in the future. However, in September, 2010 the U.S. DOT and EPA issued a Notice of Intent to establish fuel economy and GHG emissions regulations from 2017 - 2025, and an NPRM for these standards is expected in 2011. Such a rule will more than double the horizon of regulation from the current six years. Accurate predictions of the production readiness of powertrain technology will be critical to identifying optimal levels of regulation. Such a task will test the limits of NHTSA's technology adoption-based modeling approach, and the very real possibility exists that a presently unknown technology could be developed, commercialized and produced prior to end of the regulated period.

5.4 Other Considerations

The deployment scenarios described in this thesis could reasonably be used to describe a broad range of future vehicle features and technologies. However, they are examples of relatively straightforward, standalone systems developed by automakers and their suppliers. Automotive developments that will not necessarily follow the patterns exemplified here are described below.

5.4.1 Alternative Fuels and Parallel Innovation

One of the most critical questions regarding future automotive technology is whether such deployment rates could be used to describe future powertrain technologies. For features of a similar level of complexity (advanced injection or induction systems, for instance) these adoption rates are plausible. However, many powertrain technologies viewed as central to reducing fuel consumption and GHG emissions are based on alternative fuels.

Most manufacturers are now developing a range of alternative-fuel vehicles, and virtually all require some degree of parallel infrastructure development: BEVs require the development of a public charging infrastructure and major grid improvements; fuel cell vehicles require a hydrogen refueling infrastructure, and even diesel passenger cars in large numbers would require changes to the refining and refueling infrastructure.

The need for infrastructure development in parallel with automotive technology development could significantly extend the deployment rates describe here for two primary reasons. The parallel deployment of technology by at least two giant industries would require close alignment of incentives not typically seen. Additionally, the need for infrastructure development implies that consumers will initially have limited access to such infrastructure, negatively impacting two of Rogers' key adoption factors: compatibility and trialability.

5.4.2 Disruptive Innovation

The concept of disruptive innovation, introduced by Bower and Christensen (1995), illustrates the idea that a new paradigm or product will result in a simpler product that will either define a new market segment or appeal to low-end customers and gradually overtake existing producers until, one by one, they are unable to compete and the market is revolutionized.

The features discussed in this thesis represent *sustaining* improvements, not disruptive ones. They are, therefore, silent on the issue of the results that a large, pattern-breaking innovation in the automotive industry might achieve. Examples of major disruptive innovations have been notably absent from the automotive market and despite vast growth in capabilities, passenger cars and the infrastructure in which they are sold, serviced and operated remain fundamentally similar to that of a century ago.

[Christensen et al., 2002] set forth a brief list of tests that are helpful in identifying common themes for disruptive innovations that will create a new market:

- Test #1: Does the innovation target customers who in the past haven't been able to "do it themselves" for lack of money or skills?
- Test #2: Is the innovation aimed at customers who will welcome a simple product?
- Test #3: Will the innovation help customers do more easily and effectively what they are already trying to do?

and another set of tests for identifying if a technology is capable of disrupting a market from the bottom up:

- Test #1: Are prevailing products more than good enough?
- Test #2: Can you create a different business model?

The beginnings of disruptive innovation may now be starting not with vehicles themselves, but the vehicle ownership model. Just as automotive leasing has grown

to a major portion of the new passenger car market, new business models are forming that further distance a vehicle operator from purchase of the vehicle.

Companies such as Better Place, founded in 2007, envision a model in which battery packs and electric power are purchased as a service. Discharged battery packs are exchanged for charged ones at service stations much as barbecue users exchange empty propane tanks for full ones.

Car sharing services such as ZipCar take this concept a step further, allowing subscribers to use vehicles themselves as a service. While this business model is not inherently different from traditional car rental, careful placement of vehicles in dense urban locations, hourly rentals and online reservations have made use of service sufficiently convenient that some ZipCar members now use the service in lieu of private cars.

Battery and car sharing exemplify the traits identified by Christensen as typical of disruptive technologies. With sufficient users, car sharing services could alter vehicle sales and usage dynamics, disrupting current sales models. Such services could also fundamentally change demand for vehicle technology, perhaps pushing for faster deployment of comfort/convenience features and safety features, or perhaps a large number of cost-conscious car-sharing users could strengthen demand for fuel-saving technology.

However, disruptive technologies are notoriously hard to predict in advance. Only in retrospect may we be able to point to specific causes of innovation.

5.5 Extensions

As discussed in earlier chapters, required and optional features add significantly to the mass of a vehicle. However, some features impact vehicle efficiency in other ways. Electrical features necessitate the use of a larger alternator and charging system and impose higher parasitic losses. Vacuum and hydraulic assistance also sap power from a vehicle's engine. These effects are not captured in this thesis but are potentially quantifiable.

Chapter 4 of this thesis has focused exclusively on characterizing historical deployment rates. However, this document does not attempt to identify the limits of feasibility and with enough investment deployment rates could be pushed higher. A more complete analysis would also characterize the marginal cost curve of faster deployment of vehicle technology and features.

Appendix A

Tables

For features where take rate data is unavailable, 2010 take rates have been estimated using availability data for top-10 selling passenger cars in early 2010 as described in Chapter 2. These features and associated availability is shown in the table below. For features that have been in existence for a long time but exact introduction date is unknown, i.e. fog lamps, the year 1938 is used.

Table A.1: Common vehicle features and availability on 2010 passenger cars.

Feature	Introduction Date	Toyota Camry	Toyota Corolla	Honda Accord	Honda Civic	Nissan Altima	Ford Fusion	Chevrolet Impala	Chevrolet Malibu	Ford Focus	Toyota Prius
Trip Computer / Digital Clock	1958	S	S	S	S	S	S	S	S	S	S
Fold-down seats	1965	S	S	S	S	S	S	S	S	S	S
Remote Fuel / Trunk Release	1988	S	S	S	S	S	S	S	S	S	S
12V Power Outlets	1938	S	S	S	S	S	S	S	S	S	S
Cup Holders	1938	S	S	S	S	S	S	S	S	S	S
Readings Lights	1938	S	O	S	S	S	S	S	S	S	S
Center Console / Armrest	1938	S	S	S	O	S	S	S	S	N	S
Aux / iPod input	2001	S	S	S	O	O	S	S	S	O	S
Auto On/Off Headlamps	1952	S	N	S	N	O	O	S	S	N	S

Continued on next page

Table A.1 – continued from previous page

Feature	Introduction Date	Toyota Camry	Toyota Corolla	Honda Accord	Honda Civic	Nissan Altima	Ford Fusion	Chevrolet Impala	Chevrolet Malibu	Ford Focus	Toyota Prius
Rear Headrests	1968	S	N	S	N	N	N	S	S	O	S
15" Wheels	1938	N	S	N	S	N	N	N	N	S	S
16" Wheels	1938	S	O	S	O	S	S	N	N	O	N
17" Wheels	1938	O	O	O	O	O	O	S	S	O	O
18" Wheels	1938	N	N	O	N	N	O	O	O	N	N
19" Wheels	1938	N	N	N	N	N	N	N	N	N	N
20" Wheels	1938	N	N	N	N	N	N	N	N	N	N
Wood / Metal Interior Trim	1938	O	O	O	N	S	O	S	S	O	N
Illuminated Entry	1983	O	O	N	N	N	O	S	S	O	S
Body Kit	1938	O	O	O	O	O	O	O	O	O	S
Rear Spoiler	1938	O	O	O	O	O	O	O	O	O	S
Fog Lamps	1938	O	O	O	O	O	O	O	O	O	O
Multi-Beam / HID headlamps	1991	S	N	N	N	O	S	N	N	N	O
Overhead Console	1938	O	N	N	N	S	N	N	N	N	S
Universal Garage Door Opener	1983	O	N	O	N	O	N	O	O	N	O
Trunk Organizer	1938	S	N	N	N	N	N	N	N	N	N
Rear Sunshade	1938	O	N	N	N	N	N	O	O	N	N
Active Cruise Control	1995	N	N	N	N	N	N	N	N	N	O
Lane Departure Warning	2004	N	N	N	N	N	N	N	N	N	O
Blind Spot Detection	2007	N	N	N	N	N	O	N	N	N	N
Rain-Sensing Wipers	1996	N	N	N	N	N	N	N	N	N	N
Night Vision Camera	2007	N	N	N	N	N	N	N	N	N	N
Semi-Automatic Gearbox	1997	N	N	N	N	N	N	N	N	N	N
Power Rear Seats	1979	N	N	N	N	N	N	N	N	N	N
Variable Ratio Steering	1969	N	N	N	N	N	N	N	N	N	N
Heated Steering Wheel	1999	N	N	N	N	N	N	N	N	N	N
Active Headlamps	2003	N	N	N	N	N	N	N	N	N	N
Soft-Close trunk	1991	N	N	N	N	N	N	N	N	N	N
Soft-Close doors	1991	N	N	N	N	N	N	N	N	N	N

Continued on next page

Table A.1 – continued from previous page

Feature	Introduction Date	Toyota Camry	Toyota Corolla	Honda Accord	Honda Civic	Nissan Altima	Ford Fusion	Chevrolet Impala	Chevrolet Malibu	Ford Focus	Toyota Prius
Power Adj. Wheel	1965	N	N	N	N	N	N	N	N	N	N
Side-View Cameras	2007	N	N	N	N	N	N	N	N	N	N
Rain-Sensing Wipers	1996	N	N	N	N	N	N	N	N	N	N

Appendix B

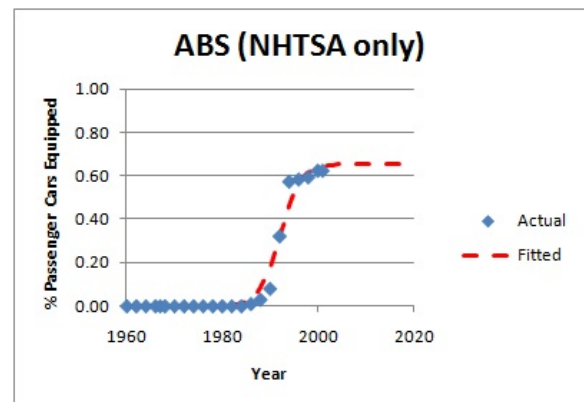
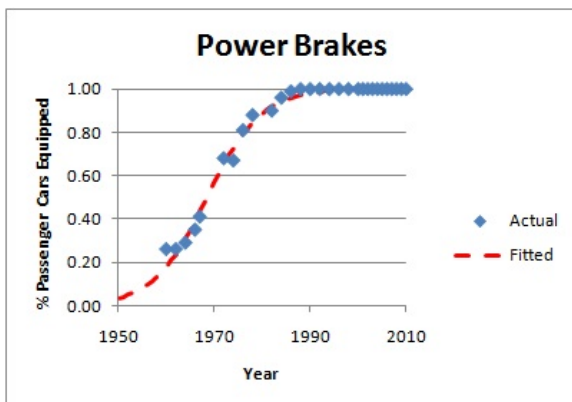
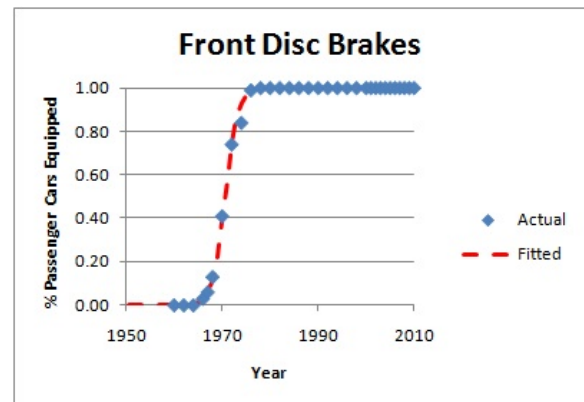
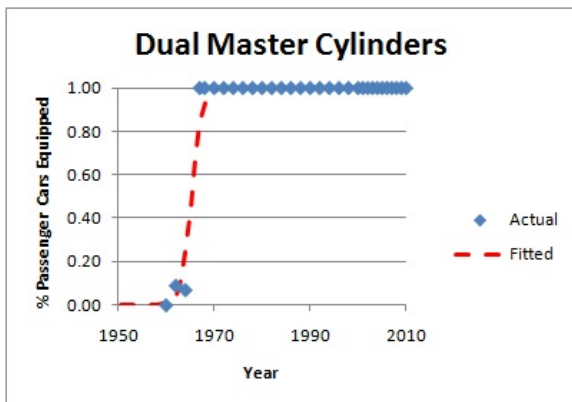
Mass Decomponding Studies

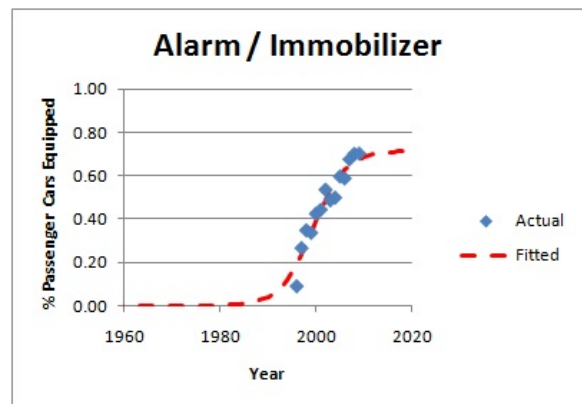
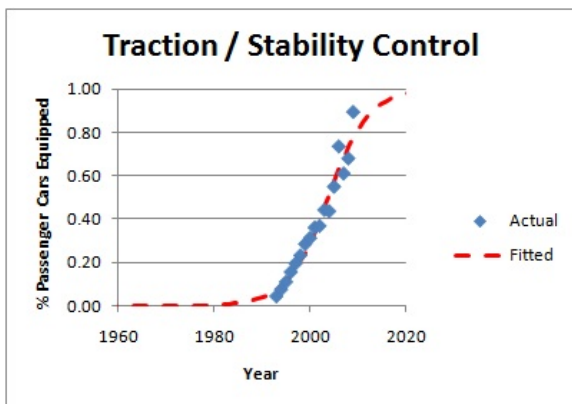
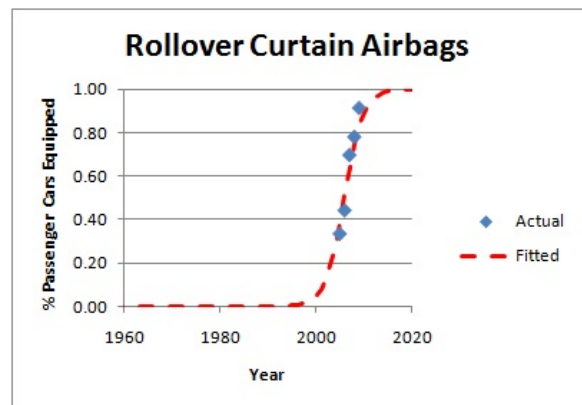
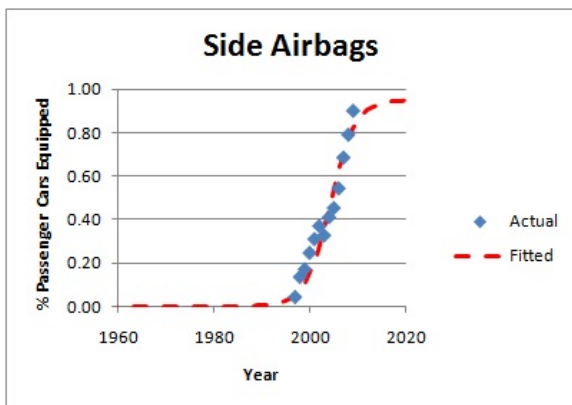
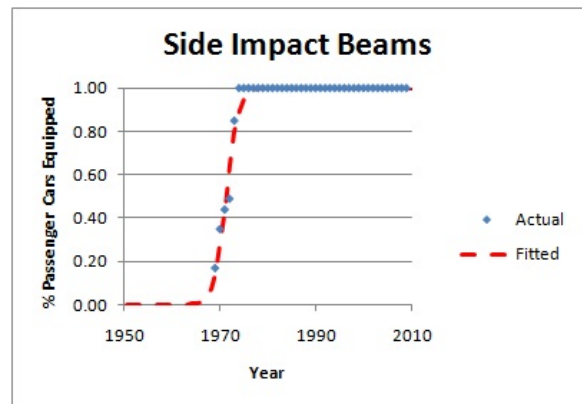
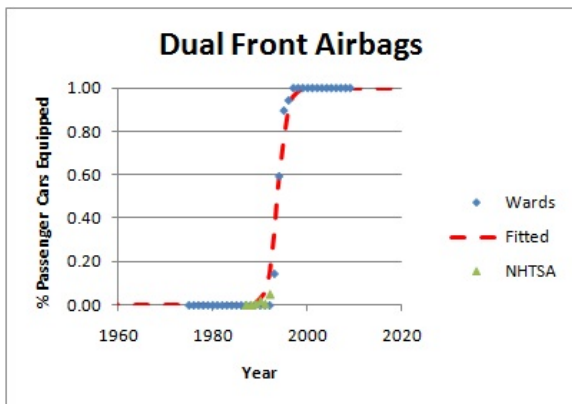
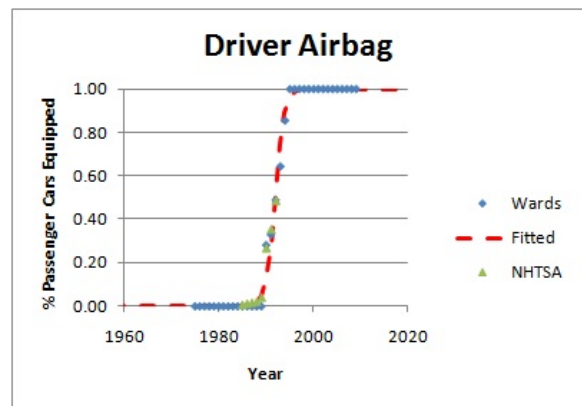
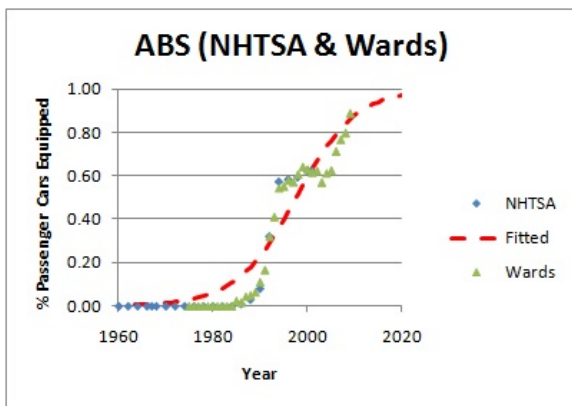
Table B.1: Literature that cites the concept of secondary mass savings, uses it in an analysis of vehicle lightweighting or attempts to quantify it. Updated and expanded from [Bjelkengren, 2008]

Mass compound- ing Coeffi- cient	Method Used	Reference
23% - 56%	Audi experience	[International Aluminum Institute, 2007, European Aluminum Association, 2008]
140%	Renault engineer opinion	[Daniels, 1987]
50%	industry expert opinion	[Office of Technology Assessment, 1995]
50%-70%	industry rule of thumb	[Patton and Edwards, 2002]
50%-100%	referenced literature	[Lloyd and Lave, 2003]
50%	referenced literature	[Lorenz, 2005]
50%-80%	referenced literature	[Asnafi et al., 2003]
50%	industry rule of thumb	[Das, 2005]
25%	physical modeling of VW Lupo 1.4 model lightweighted with Carbon Fiber Reinforced Plastic (CFRP)	[Van Acker, 2009, J. R. Duflou et al., 2009]
52%	physical modeling of prototype Ford Mercury Sable	[Stodolsky, F. et al., 1995]
64%-68%	physical vehicle modeling	[Bull et al., 2008, Aluminum Transportation Group, 2006]
54%	statistical regression	[Artinian and S. L. Terry, 1961]
108%-134%	statistical regression	[Adams, D. G. et al., 1975]
72%-212%	statistical regression	[GM Cost of Weight Task Force, 1975, Padovini and GM Corporate Mass Core Group, 1981]
123%-147%	statistical regression and calculation of loads	[Kato and Shiroi, 1992]
70%-180%	statistical regression	[Malen and Reddy, 2007]
82%-129%	statistical regression	[Bjelkengren, 2008, Bjelkengren, C. et al., 2008, Lee, 2010]

Appendix C

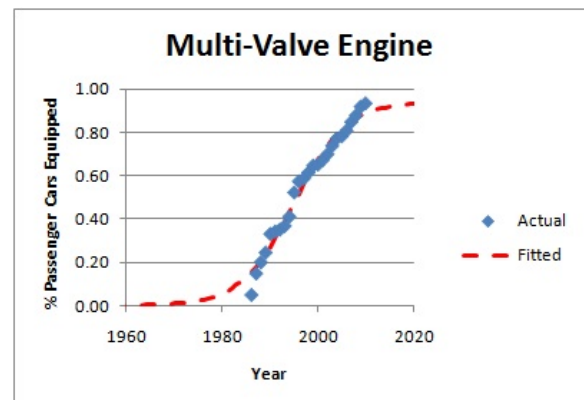
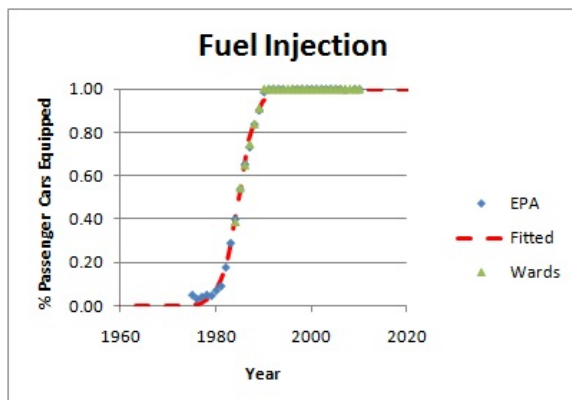
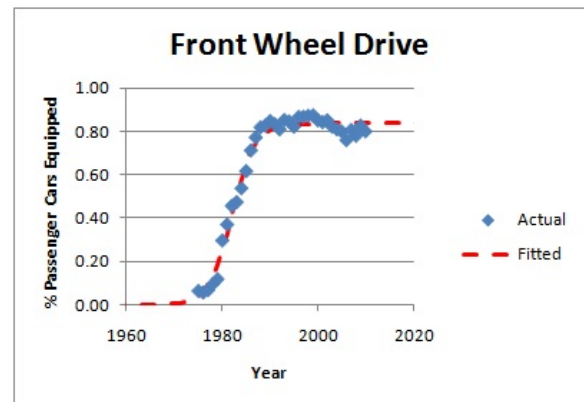
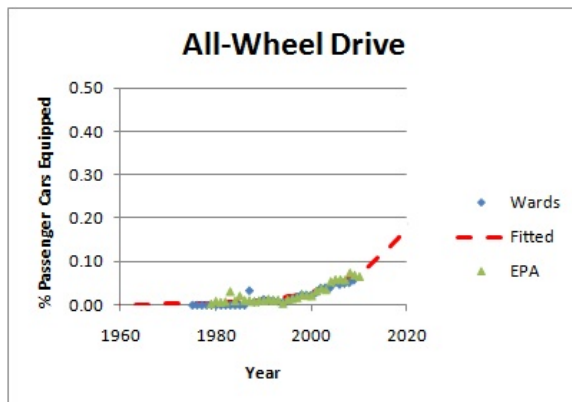
Safety Features: Take Rates and Regression

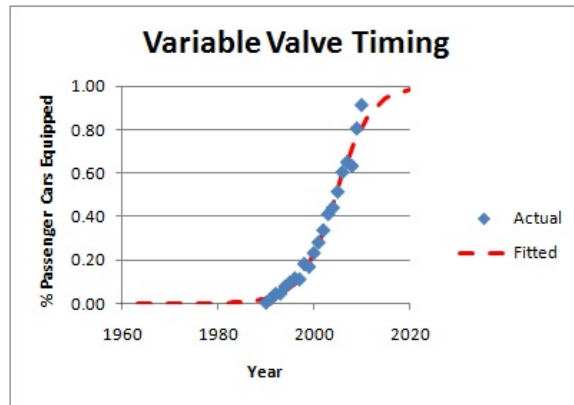




Appendix D

Powertrain Features: Take Rates and Regression

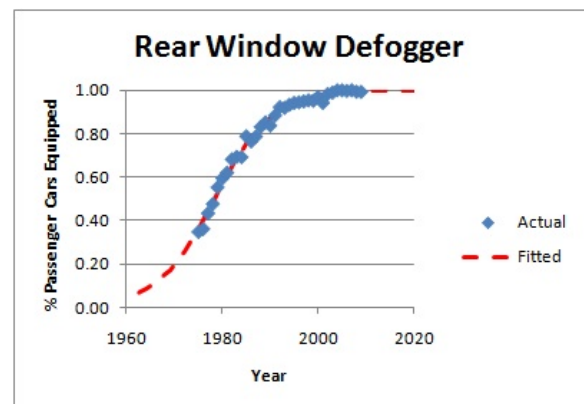
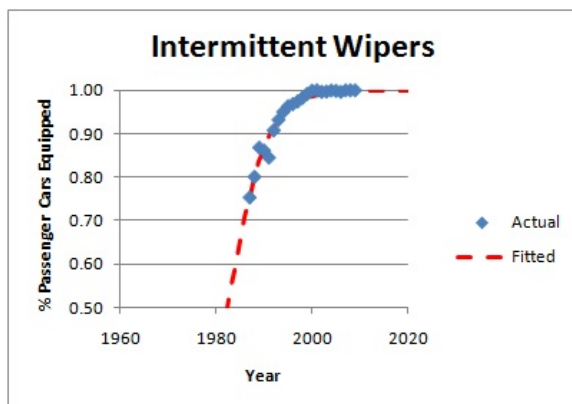
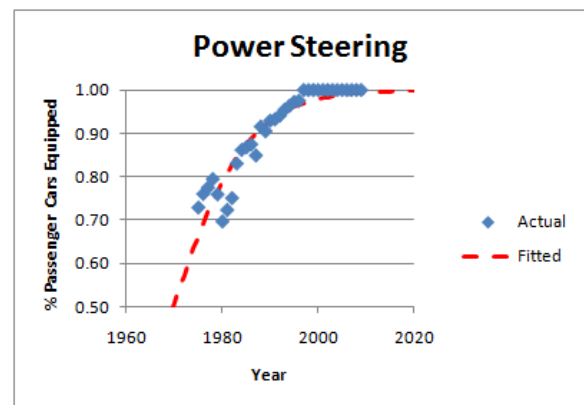
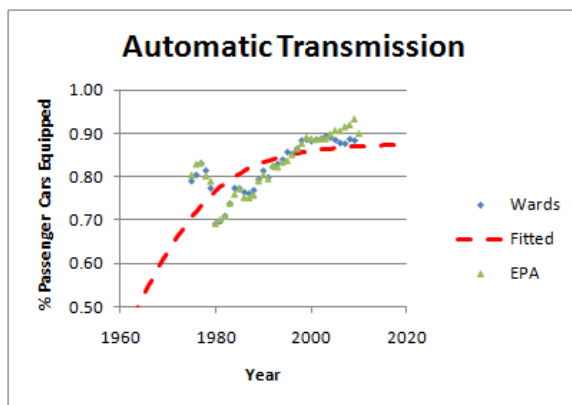


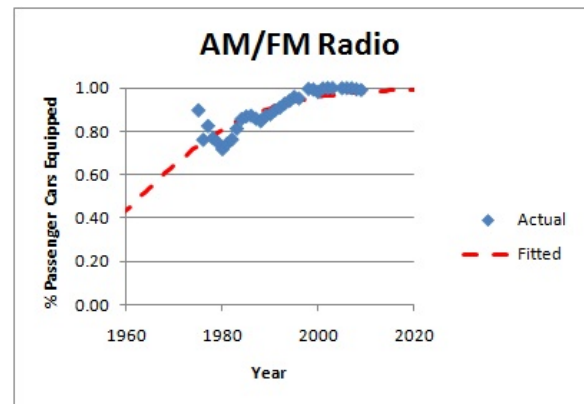
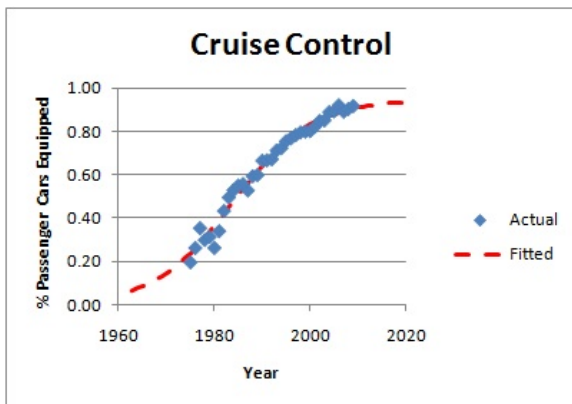
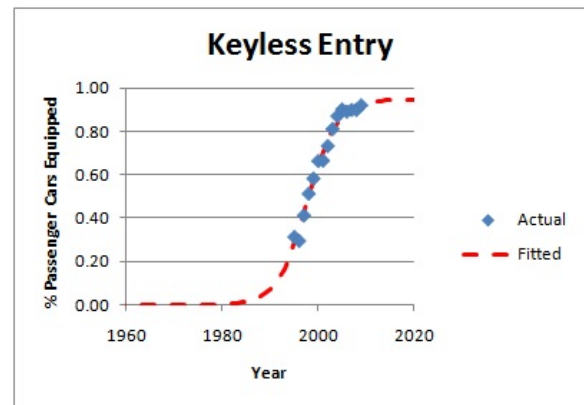
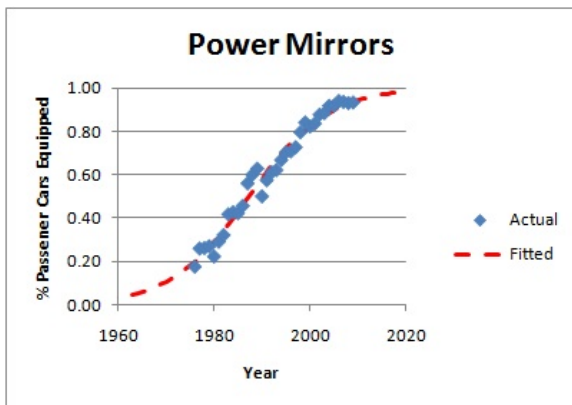
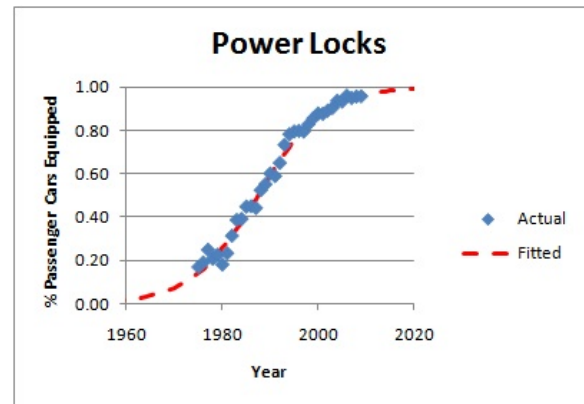
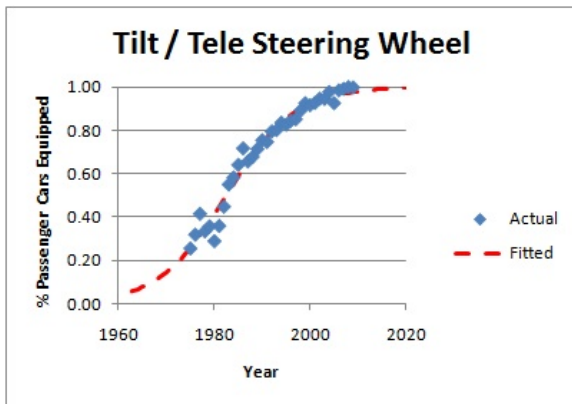
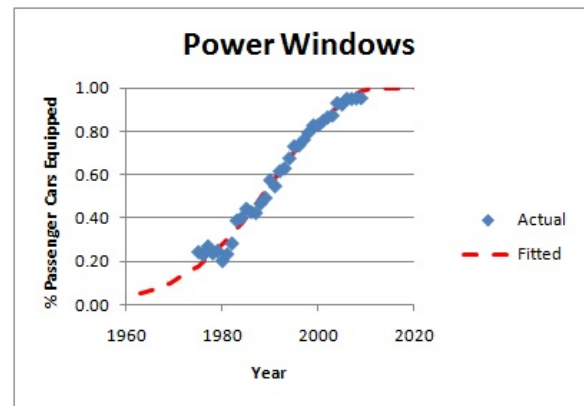
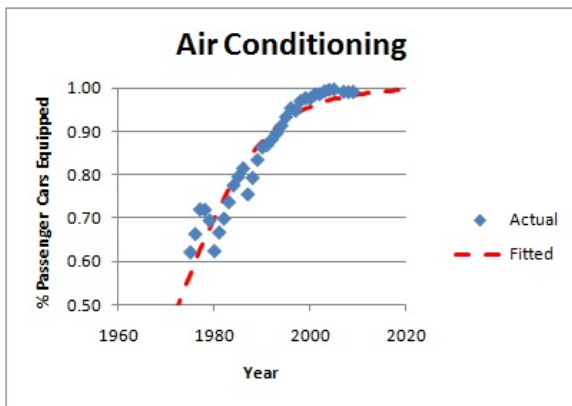


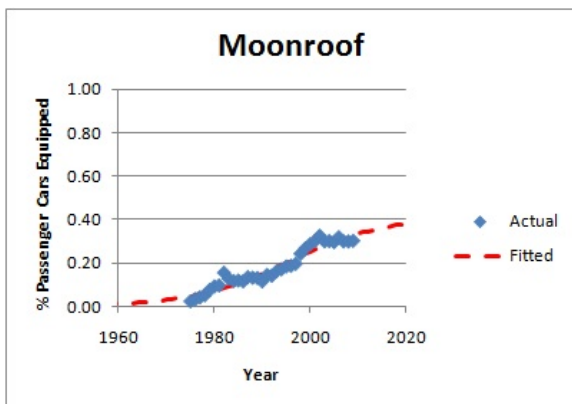
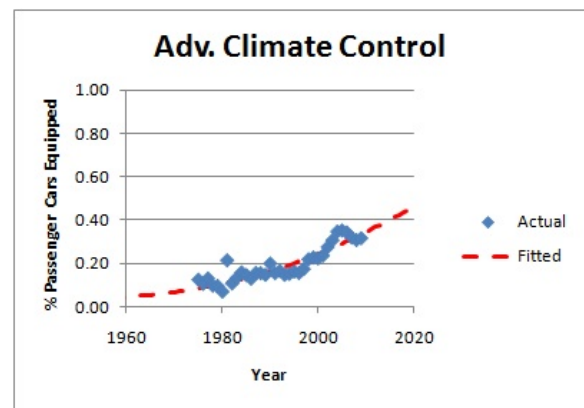
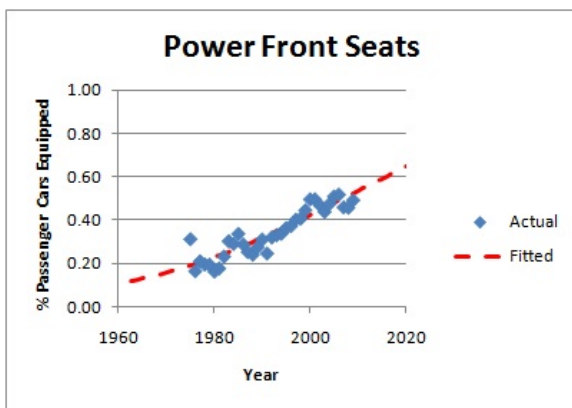
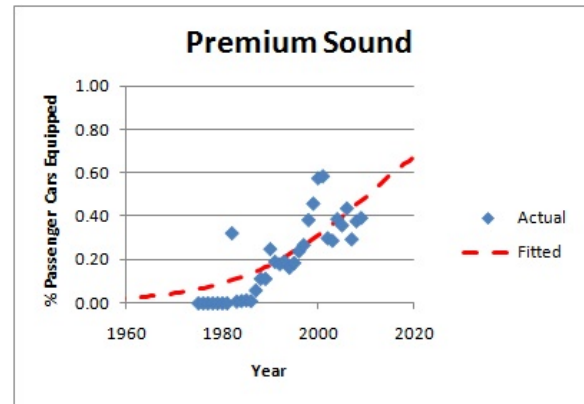
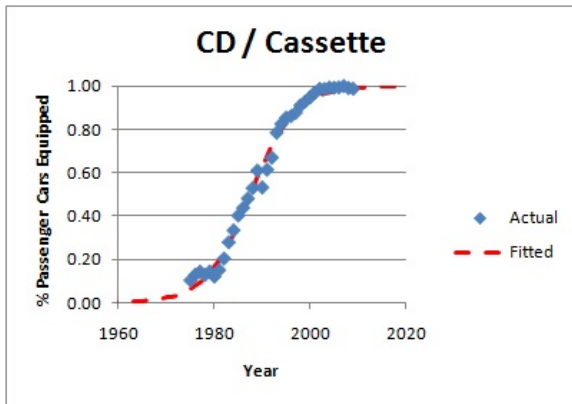
Appendix E

Comfort and Convenience

Features: Take Rates and Regression



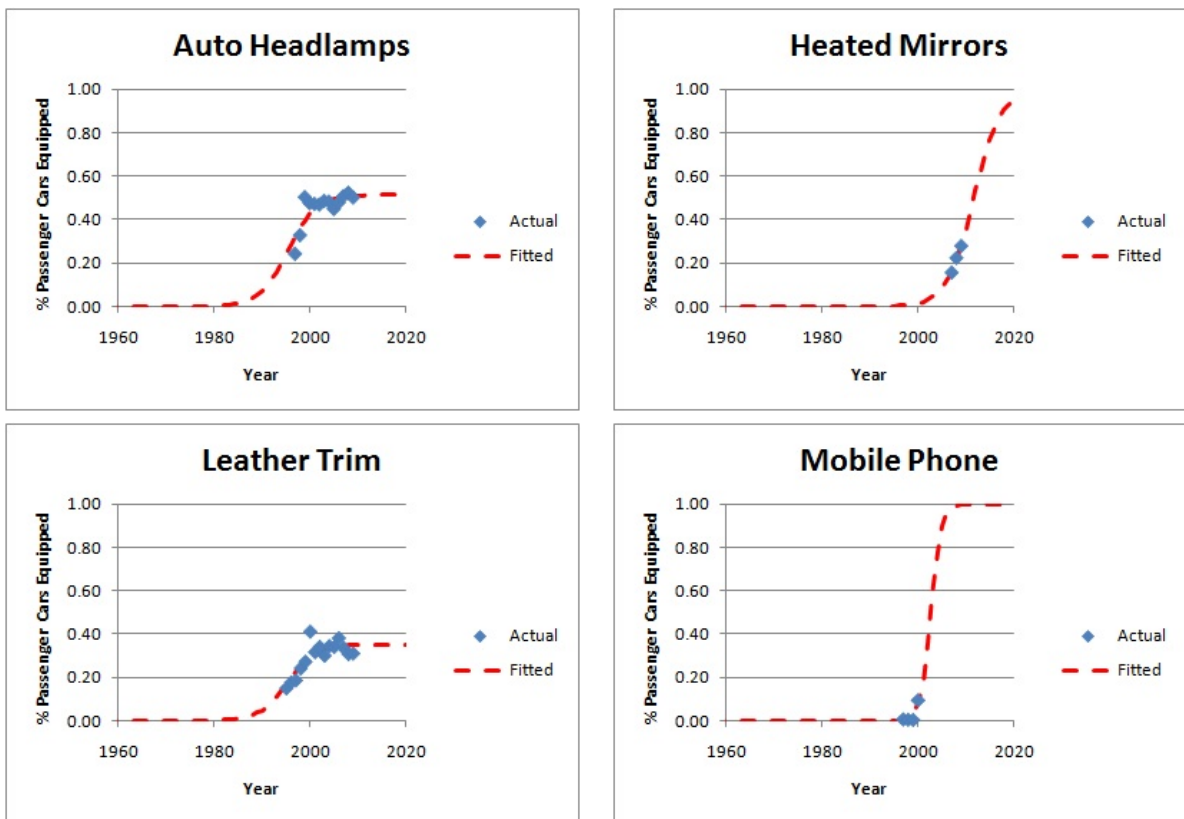


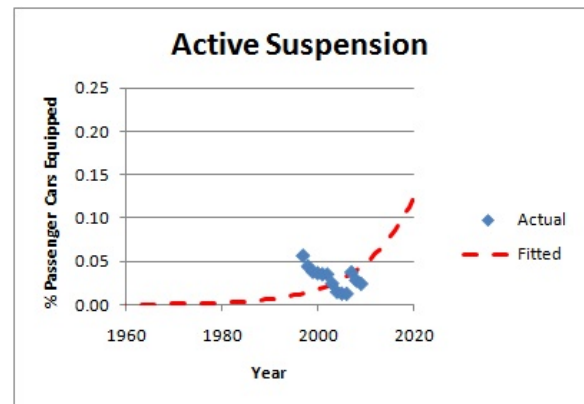
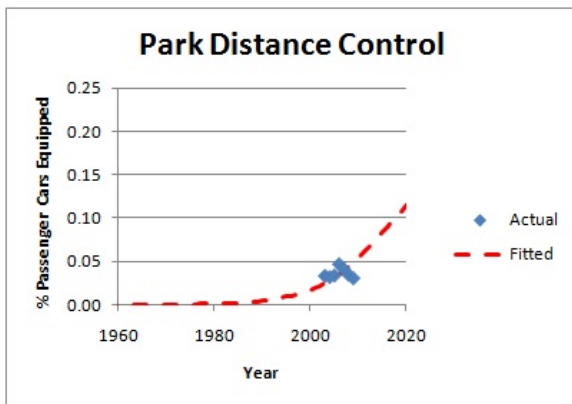
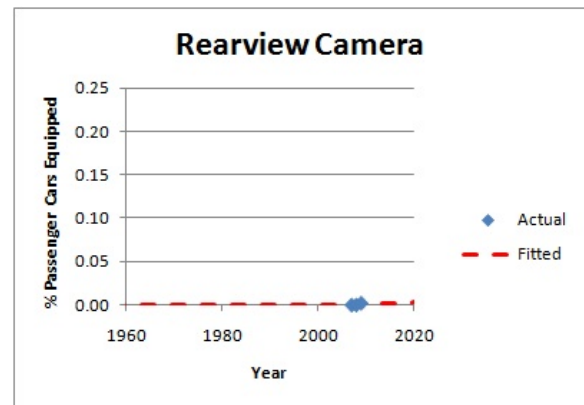
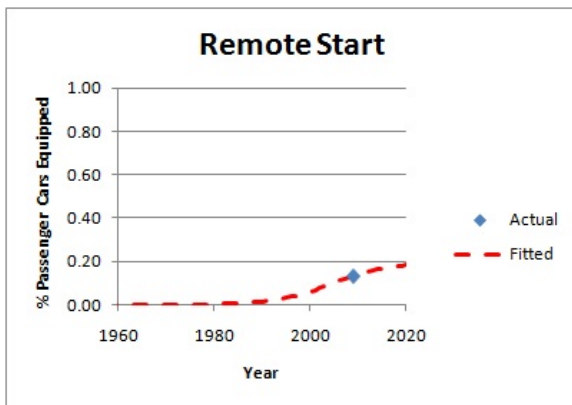
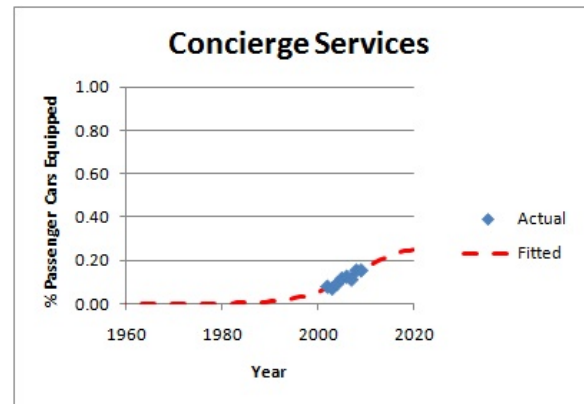
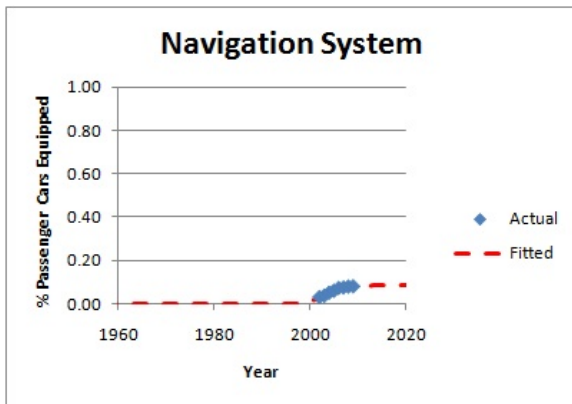
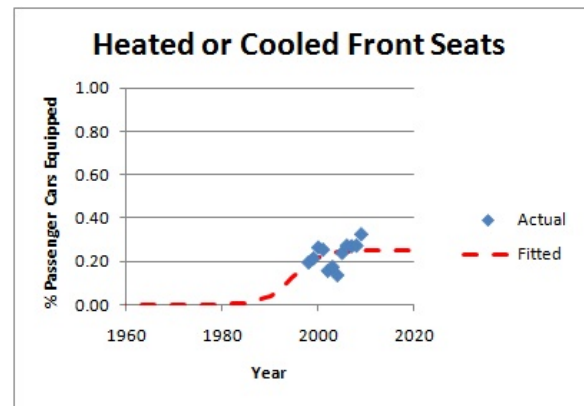
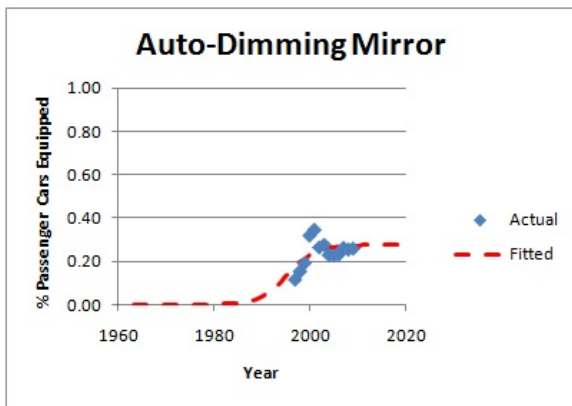


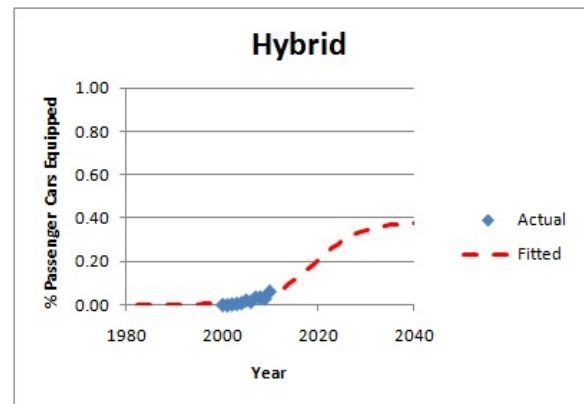
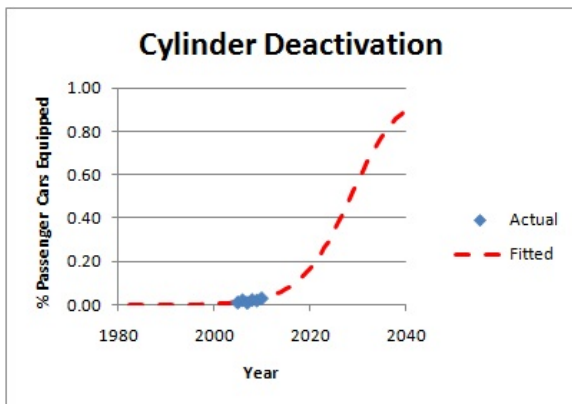
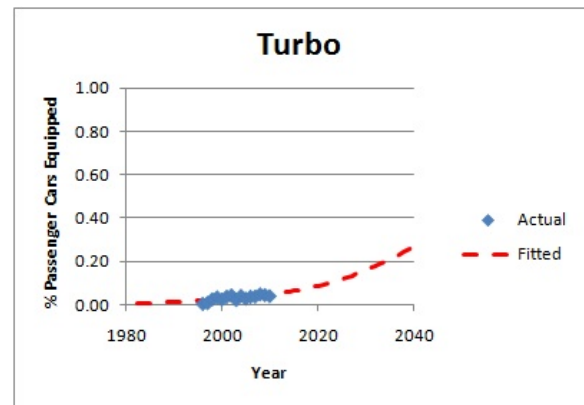
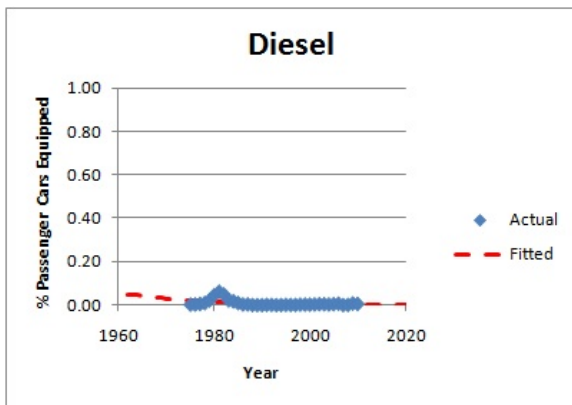
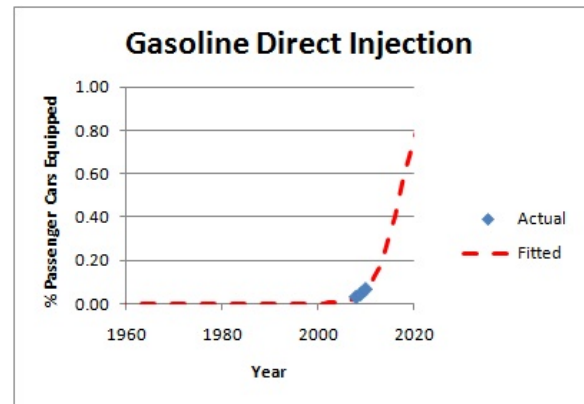
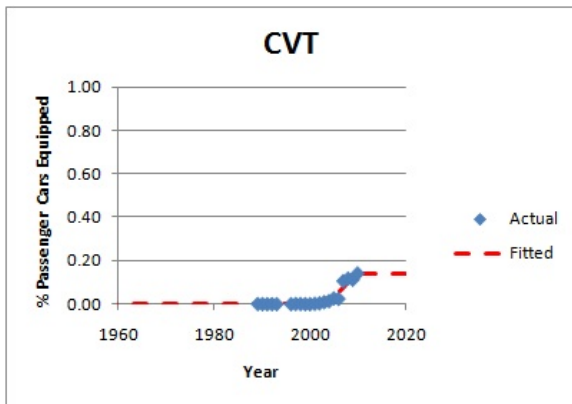
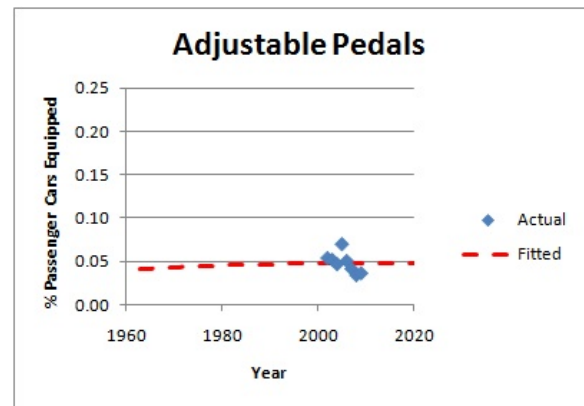
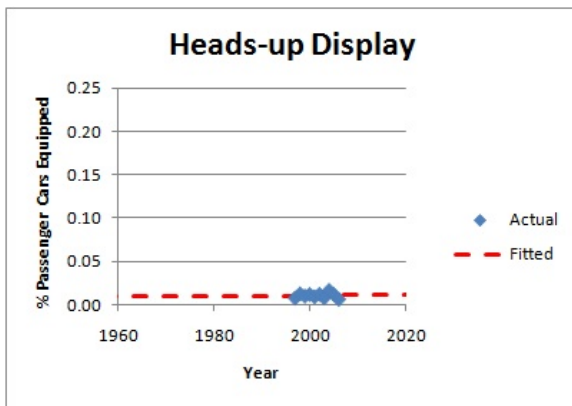
Appendix F

Other: Features with Limited Data

Due to limited data availability the deployment trends shown here are not included in analyses in Chapter 4. However, some of these features are used for mass analysis in Chapter 2.







Appendix G

Regression Data Points

Table G.1: This table includes data points and regression values for features logistic regressions analyzed in Chapter 4.

Feature	Category	Required?	Introduction (year, approx.)	Max Growth (year, fit)	Max Growth (%/year, fit)
Automatic Trans- mission	Comfort/Convenience	No	1940	1961	2.2%
Power Steering	Comfort/Convenience	No	1951	1970	3.2%
Intermittent Wiper/Washers	Comfort/Convenience	Yes	1963	1983	6.1%
Rear window defog- ger	Comfort/Convenience	Yes	1938	1979	4.2%
Air Conditioning	Comfort/Convenience	No	1939	1973	2.8%
Power Windows	Comfort/Convenience	No	1940	1990	3.2%
Tilt/Telescopic Wheel	Comfort/Convenience	No	1965	1983	3.5%
Power Locks	Comfort/Convenience	No	1956	1988	3.6%
Power Mirrors	Comfort/Convenience	No	1946	1988	3.1%
Keyless Entry/SmartKey	Comfort/Convenience	No	1983	1998	7.7%
Cruise Control	Comfort/Convenience	No	1958	1984	2.9%
AM/FM Radio	Comfort/Convenience	No	1932	1964	2.1%
CD/Cassette	Comfort/Convenience	No	1965	1988	5.3%
Premium Sound	Comfort/Convenience	No	unknown	2011	1.9%
Power Front Seats	Comfort/Convenience	No	1946	2007	1.1%
Advanced Climate Control	Comfort/Convenience	No	1954	2024	1.2%
Moonroof	Comfort/Convenience	No	1956	1996	1.0%
Satellite Radio	Comfort/Convenience	No	2002	2010	11.6%
Rear DVD Player	Comfort/Convenience	No	1998	2019	0.8%
Front Wheel Drive	Powertrain	Partial	1929	1983	8.7%
Four Wheel Drive	Powertrain	No	1905	2036	2.4%
Fuel Injection	Powertrain	Yes	1955	1985	13.4%
Multivalve	Powertrain	Yes	1922	1995	4.3%
VVT	Powertrain	Yes	1970	2005	6.6%
Dual Master Cylin- ders	Safety	Yes	1921	1966	22.5%
Front Disc Brakes	Safety	Yes	1949	1971	19.1%
Power Brakes	Safety	Yes	1928	1969	4.5%
Anti-Lock Brakes	Safety	Pending	1971	1998	4.0%
Driver Front Airbag	Safety	Yes	1981	1990	23.9%
Dual Front Airbags	Safety	Yes	1987	1994	23.9%
Side Impact Beams	Safety	Yes	unknown	1972	19.2%
Side Airbags	Safety	No	1995	2005	9.0%
Curtain Airbags	Safety	Pending	1998	2006	12.5%
Traction / Stability Control	Safety	Pending	1971	2004	5.9%
Alarm / Immobi- lizer	Safety	Yes	1920	2000	5.3%

Table G.2: Relevant parameters for Z curve fit on feature time series data. CC = Comfort/Convenience, PT = Powertrain, SAF = Safety.

Feature	Category	Regulated?	Develop	Deploy	Ratio
Automatic Trans- mission	CC	No	1	40	0.0
Power Steering	CC	No	3	31	0.1
Intermittent	CC	Yes	12	16	0.7
Wiper/Washers	Comfort/Convenience	Yes	29	24	1.2
Rear window defog- ger					
Air Conditioning					
Power Windows					
Tilt/Telescopic	CC	No	4	29	0.1
Wheel	CC	No	18	28	0.7
Power Locks					
Power Mirrors					
Keyless Entry/SmartKey					
Cruise Control	CC	No	10	33	0.3
AM/FM Radio	CC	No	8	48	0.2
CD/Cassette	CC	No	14	19	0.7
Premium Sound	CC	No	unknown	unknown	N/A
Power Front Seats	CC	No	16	91	0.2
Advanced Climate Control	CC	No	28	83	0.3
Moonroof	CC	No	19	41	0.5
Satellite Radio	CC	No	4	8	0.5
Rear DVD Player	CC	No	11	21	0.5
Front Wheel Drive	PT	Partial	49	10	5.1
Four Wheel Drive	PT	No	110	42	2.6
Fuel Injection	PT	Yes	26	7	3.5
Multivalve	PT	Yes	62	22	2.8
VVT	PT	Yes	17	15	1.2
Dual Master Cylin- ders	SAF	Yes	43	4	9.6
Front Disc Brakes	SAF	Yes	19	5	3.7
Power Brakes	Safety	Yes	30	22	1.3
Anti-Lock Brakes	SAF	Pending	15	25	0.6
Driver Front Airbag	SAF	Yes	9	4	2.1
Dual Front Airbags	SAF	Yes	5	4	1.2
Side Impact Beams	SAF	Yes	unknown	unknown	N/A
Side Airbags	SAF	No	5	11	0.4
Curtain Airbags	SAF	Pending	4	8	0.5
Traction / Stability Control	SAF	Pending	25	17	1.4
Alarm / Immobi- lizer	SAF	Yes	73	13	5.4

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