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Driving Behavior of Hybrid Bus

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Driving behavior of hybrid bus

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DEDICATION

I would like to dedicate this thesis to my parents. Without their support and encouragement, I could not complete this process. In addition, this thesis is also dedicated to my fiancée, who was accompanied with me in library during numerous weekends.

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DISCLAIMER

This document was prepared and written by the author to fulfill the requirements set forth by Iowa State University for the degree of Master of Science. The views expressed in this thesis are those of author and do not reflect the viewpoint or policy of Institute for Transportation (InTrans), CyRide Transit Agency, Iowa Energy Center, or Iowa State University (ISU).

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ABSTRACT

Transportation consumed 71% of oil consumption and produced 27% of greenhouse gas in the United States in 2012. In addition, transportation also accounts for 50 %, 31.9%, 21.5%, and 1% in carbon monoxide, nitrogen oxides, volatile organic compounds, and sulfur dioxide respectively in the U.S. Due to soaring fuel prices and environmental concerns, hybrid vehicle technology attracts more and more attentions in recent years. The electric motor on hybrid bus converts braking power into electricity during deceleration, which could be used later during acceleration. Therefore, the research hypothesis is that the driver' driving behavior are closely related to the amount of electricity generated, which is directly related to fuel economy. Therefore, this thesis designed the study to test the variability in driving behavior parameters. However, the impact of those driving behavior parameters on fuel economy is recommended to be investigated in future research.

In order to measure the bus driving activities, six GPS data loggers were installed on three hybrid buses and three control buses. The data was collected on ten weekdays from November 29 to December 12, 2011. Two routes were chosen in this study, which are arterial route and campus route. Several variables were created to characterize driving behaviors, including acceleration, deceleration, and vehicle specific power (VSP), etc. Nonparametric analysis of variance method was used to test the variability in driving behavior parameters. The results showed that the driver had the dominant impacts on most driving behavior parameters. The comparison test also found the hybrid buses accelerated slower than regular diesel bus. In addition, the regression model was also built to fit the same dataset. The model results from both nonparametric method and regression method did not agree with each other for some driving behavior variables since they used different model estimation techniques. It is recommended to draw conclusion based on nonparametric model because it requires fewer assumptions with more statistical power. In conclusion, this study found the driving behavior was statistically different among drivers, and it is recommended to evaluate how those differences in driving behavior affect the fuel economy and emissions of hybrid buses in future research.

Keywords: Hybrid electric-diesel Bus, Regular Diesel Bus, Driving Behavior, Nonparametric ANOVA, Regression Model.

CHAPTER 1 INTRODUCTION

Section 1.1 briefly summarizes the energy and environmental issues that motivate us to study the driving behavior of hybrid bus. Section 1.2 discusses the objectives of this study. Section 1.3 presents thesis organization.

1.1 Motivation

The primary function of transportation is to move people and freights from one location to another to overcome the geographical inequality of resources allocation, in a safe, timely, and efficient manner. Since the internal combustion engine was developed in 20th century, people started to exploit petroleum to support the new way of transportation powered by internal combustion engines. Nowadays, U.S. economy has unprecedented dependence on petroleum oil than ever. The United States consumed approximately 18,835,000 barrels of oils per day in 2011 according to U.S. Energy Information Administration, while nearly 60% of them were imported.

In addition to large petroleum demanding, transportation is also one of the biggest contributors to emission issues. In 2012, Environmental Protection Agency (EPA) reported the transportation accounts for 50 %, 31.9%, 21.5%, and 1% in carbon monoxide, nitrogen oxides, volatile organic compounds, and sulfur dioxide respectively. Several studies found direct relationship between vehicular emissions and human health conditions. As such, people start to look for clean vehicle technologies that could reduce the dependence on foreign petroleum oil and also produce less emission for a sustainable transportation system.

In order to address those issues, U.S. Department of Transportation (DOT) proposed a number of strategies, including the introduction of bio-renewable fuels, deployment of clean vehicle technologies, and legislation of stricter policies, etc. In recent years, U.S. has been started to deploy hybrid buses in several transit agencies across the country. As shown in figure 1.1, American Public Transit Administration (2011) projected the distribution of bus power sources and found approximately 4,000 hybrid electric buses were deployed or planned to be in service in 2008.

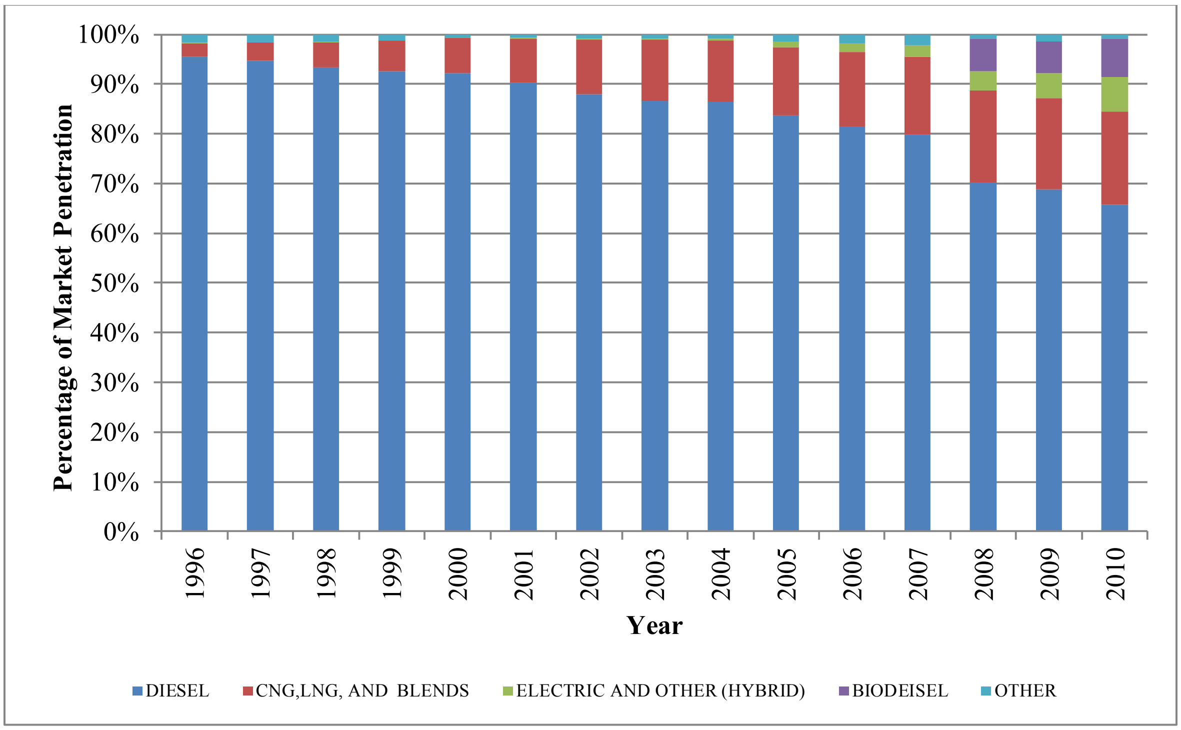


Figure 1.1 The distribution of power sources for transit buses in 2008

Source: Annual APTA Public Transportation Vehicle Database

1.1.1 Large Demanding in Petroleum Oil

According to the National Transportation Statistics (2011), the transportation sector accounts for approximately 28% of all energy consumption in the United States. The demanding of petroleum oil is expected to continue growing in future years, even though a small decline was observed during recent economic recession in 2008. Although U.S. market has large demanding on petroleum oil, the domestic market could only provide approximately 40% of them. Energy Information Administration (2012) estimated the gap between U.S. petroleum production and the petroleum demanding is 10.8 million barrels per day.

The highly dependence of petroleum oil on foreign countries brought many unstable factors to the U.S. national security and economy growth. Hence, the reduction the dependence on petroleum oil is one of primary goals for the U.S. Due to the active cooperation among different parties, a shift of energy sources from petroleum oil to clean energy had been observed in recent years.

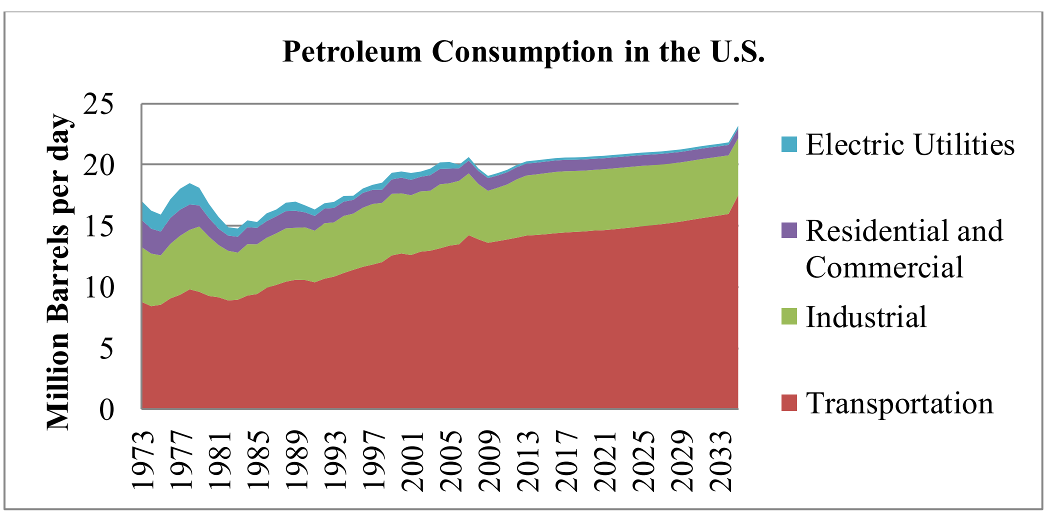


Figure 1.2 Petroleum production and consumption by end-use sectors

Source: Transportation Energy Data Book, 30th Ed.

The petroleum consumption in transportation sector decreased from 97 % to 94 % between 2004 and 2009 due to the introduction of hybrid vehicle technology, biodiesel, and compressed natural gas (CNG), etc. (Davis, 2011).

1.1.2 Transportation Emissions

The development of hybrid bus technology could also help reduce the scope of emissions issues. The development of hybrid technology in bus market could help reduce particular matter (PM) pollutants since the diesel buses contribute a majority of particular matters emission in the U.S. The electric motor on hybrid bus could assists diesel engine to operate at its optimum efficiency range, which reduces emissions.

Emissions usually refer to a complex mixture of gases and particles generated from incomplete combustion process. A number of studies found strong correlations between emission levels and human health conditions. National Ambient Air Quality Standards (NAAQS) was last amended in 1990s to regular six major vehicular pollutants, which include carbon monoxide, lead, nitrogen dioxide, ground-level ozone, particulate matter and sulfur dioxide. The impacts of those six pollutants on human health are listed below (EPA, 2012):

1) *Carbon Monoxide (CO).* Transportation contributes two third of the CO production in the United States. It is generated by incomplete combustion of fuels as a colorless and odorless gas. Over exposure to carbon monoxide may cause damage to the central nervous system.

2) *Lead (Pb).* Lead emissions can be breathed into lungs and accumulated in the bones. Lead has negative impact on nervous system, kidney function, and immune system.

Due to the regulatory efforts since 1995, the lead emissions have been decreased by 95 percent.

3) *Nitrogen Dioxide (NO_x)*. Diesel vehicles emitted 42% of the on-road nitrogen dioxide emission in the U.S (EPA, 1999). Nitrogen dioxide is a very reactive gas that can form ground level ozone under sunlight.

4) *Ground-level ozone (O_3)*. Ground-level ozone impacts adversely on human health conditions even at low concentration. Ground-level ozone can irritate the air ways and cause shortness of breath, asthma, and lung inflammation.

5) *Particulate Matter (PM)*. Particulate matters are extremely small solid or liquid particles. Due to their small size, the particles can be suspended in air and easily breathed into lungs. This could cause asthma and chronic bronchitis.

6) *Sulfur Dioxides (SO_2)*. Sulfur dioxide is highly reactive gas, which has negative impact on respiratory system, including bronchoconstriction and aggravated asthma. SO_2 can also form acid rain, which directly damages human health and pollutes the public water sources.

1.1.3 Global Climate Warming

Carbon dioxide is recognized as indicator for greenhouse gas (GHG). GHG increases the severities of storms, draughts, floods, heat waves, spread of pests, forest fires, and changes in agricultural productivity (Department of Transportation, 2010). As shown in figure 1.3, transportation sector produces 29 % of greenhouse gas emissions in the U.S. The introduction of hybrid electric-diesel bus could potentially reduce the greenhouse gas from transportation sector.

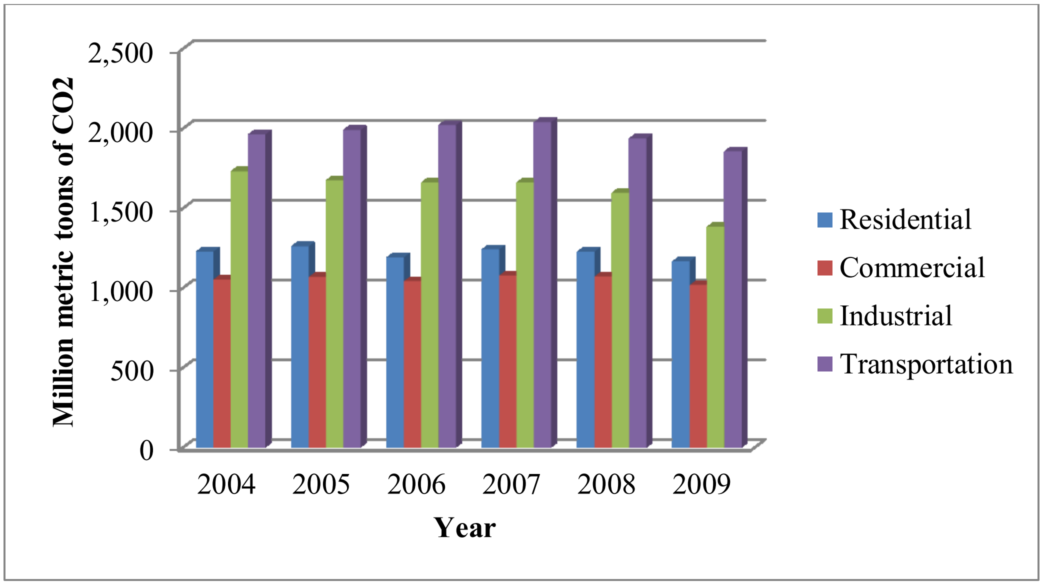


Figure 1.3 U.S. energy related greenhouse gas emissions by end-use sector

Source: Transportation Role in Reducing U.S. Greenhouse Gas Emissions, DOT 2010.

1.2 Research Objective

CyRide is a transit agency that operated by the city of Ames and Iowa State University. On August 31, 2011, Iowa State Daily reported that CyRide faced $250,000 budget deficits due to recent increasing in diesel fuel prices, which might result in rising fare and cutting service. In order to address this issue, CyRide received the transportation Investment Generating Economic Recovery (TIGGER) grant and purchased 12 hybrid transit buses in the summer of 2010. However, CyRide still did not understand how hybrid buses and regular buses drive differently.

The hybrid electric diesel bus is a relative new technology that was commercially available in late 1990s. Hybrid buses have two power sources, including a diesel engine and electric motor. During deceleration, the electric motor will be used as a generator to convert braking energy into electricity, which will be stored in battery pack on hybrid bus. During acceleration, the electric motor assists internal combustion engine to operate at its optimum range, while the diesel engine is used for maintaining speeds. Therefore, the driving behavior plays an essential role in collecting braking energy and the providence of electricity for acceleration. Ideally, the fuel flow data and driving behavior data could be collected simultaneously to test the relationship between them. The original research hypotheses are in twofold:

1) Is the driving behavior different between hybrid buses and regular buses?
2) How those differences in driving behavior affect fuel consumptions?

Due to various limitations, this study exam the first research question in this thesis and the second research question will be addressed in future research.

1.3 Thesis Organization

This thesis consists of five chapters. The first chapter introduces the motivation for researchers to study hybrid bus. The second chapter reviews the key features of hybrid buses that set the background for this research. Besides, chapter two also summarizes the past studies that related to hybrid buses in three perspectives, which include fuel economy, emissions, and driving behavior of hybrid bus. The third chapter describes the data collection protocol and equipment that used during the experiment. Additionally, this chapter also presents the procedures for the data quality assurance. Chapter four first presents the exploratory analysis on the driving behavior parameters. Additionally, the nonparametric analysis and regression models were built to explain the variability in driving behavior parameters. Chapter five summarizes the findings, contributions to the state-of-arts, limitations, and recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

Section 2.1 overviews the key backgrounds on hybrid bus technology. Section 2.2 summarizes the past studies that related to fuel economy, emissions and driving behavior of hybrid bus.

2.1 An Introduction to Hybrid Bus Technology

A better understanding of hybrid bus technology could help us conduct a more appropriate experimental design. This section introduces the key features that related to hybrid buses. A hybrid vehicle is defined as a vehicle that carrying at least two power sources, such as diesel engine and electric motor. The controller and inverter determine the power splits between the two sources. In general, the development of hybrid bus technology is based on four main concepts (Northeast Advanced Vehicle Consortium, 2000):

- Recover energy lost during deceleration
- Optimize power control algorithm
- Downsize engine size
- Increase powertrain efficiency

2.1.1 Major Components of Hybrid Bus

There are six major components for typical hybrid diesel-electric bus, which includes chassis, electric drive motor, controller and inverter, energy storage system, auxiliary power unit, and auxiliary systems (Clark et al., 2009). A description of those six components is listed in table 2.1.

Table 2.1 Description of hybrid vehicle components

Hybrid Vehicle Components	Descriptions
Chassis	The body of the vehicle. Its weight and aerodynamic design will influence vehicle efficiency.
Electric Drive Motor	Creates mechanical power from electric energy to propel the vehicle.
Controller and Inverter	Regulates the amounts of DC to AC power that the drive motor provides for acceleration and receives from regenerative braking.
Energy Storage	Collects and release electrical energy and balances the average power requirement of the vehicle with the electric power generated from APU.
Auxiliary Power Unit	Converts fuel into electrical energy. May take the form of an engine/generator or fuel cell. If APU uses an engine, it could be either an internal combustion reciprocating engine or a turbine engine.
Auxiliary Systems	Various components that drain power from the power sources. Includes climate control (heating and air conditioning), lighting, wipes, compressed air and power steering.

Source: Hybrid-Electric Transit Buses: Status, Issues, and Benefits.
Federal Transit Administration

2.1.2 Hybrid Bus Classifications

There are several methods to classify hybrid buses. In this study, the hybrid buses are classified into two types, series hybrid and parallel hybrid. For series hybrid, the electric motor is the only power source to drive the wheels. The diesel engine is only used as electric power generator to convert petroleum energy into electricity.

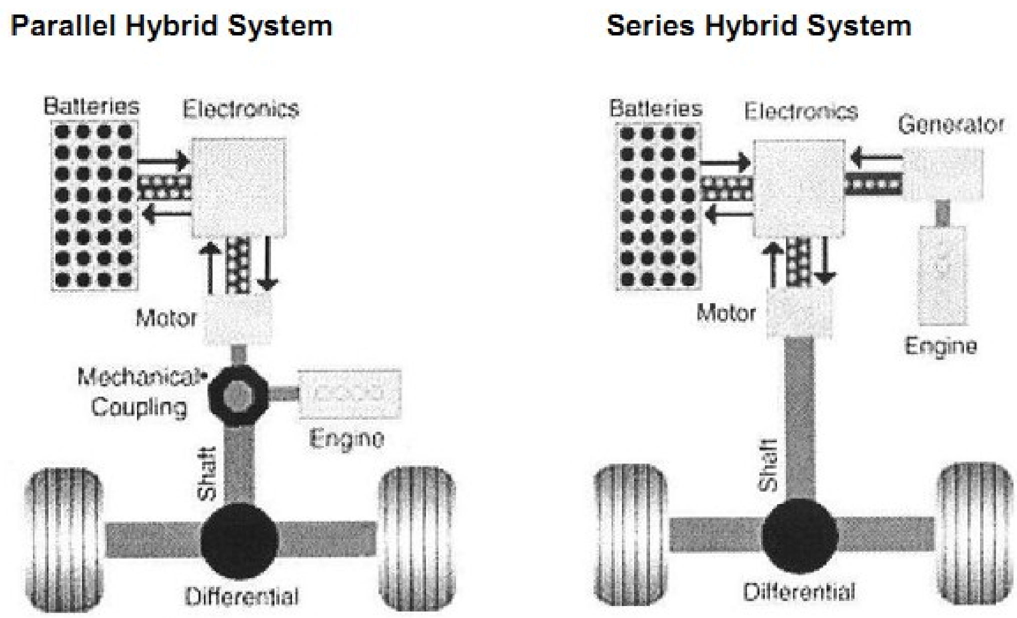


Figure 2.1 Hybrid system configuration for series and parallel design

Source: Electric Transit Vehicle Institute

For parallel hybrid design, both electric motor and diesel engine are directly connected to the wheels. This parallel design improves the efficiency by eliminate the energy conversion process from petroleum to electricity. Figure 2.1 shows the design features for both parallel hybrid bus and series hybrid bus.

2.1.2.1 Series hybrid drive train

For series hybrid drive train, the electric motor is the only power source that provides power to the wheels directly, whereas combustion engine is used to generate electric power. A summary of advantages and disadvantages of series hybrid bus are shown in table 2.2.

Table 2.2 Advantages and disadvantages of series hybrid bus

Advantages	Disadvantages
Engine configuration is relative easy and simple to control.	Most suited to city-type driving only.
Engine is able to operate at its optimum range with highest efficiency.	Large energy loss by generator and motor.
Engine is more efficient at modest speed and at high load.	Has a relatively large battery energy loss.
Allows the optimization of engine technology.	Engine, generator and motor, and battery storage device increase vehicle mass.
Can reduce severe transient load demands on the engine, which leads to lower emissions.	
Has excellent dynamic performance at low-speed acceleration.	

Source: Northeast Advanced Vehicle Consortium, 2000.

2.1.2.2 Parallel hybrid drive train

The parallel hybrid drive train provides mechanical power from both diesel engine and electric motor. A summary of advantages and disadvantages of parallel hybrid bus are shown in table 2.3.

Table 2.3 Advantages and disadvantages of parallel hybrid bus

Advantages	Disadvantages
Offers good energy during steady-state operation.	The engine cannot completely avoid transient operation because of the direct link between the engine and the wheels.
A small engine and motor help reduce vehicle mass.	Transient operation may result in higher emissions than a series hybrid system produces.
Performs well in high average power and high load conditions.	The design and control is relatively more complex than the series configuration.
Offer a good design compromise where both stop-and-go and cruising operations are likely.	Less braking energy can be captured because motor for parallel system is smaller in size than motor for series system.

Source: Northeast Advanced Vehicle Consortium, 2000.

2.2 Existing Studies

The section 2.2 reviews the past studies that related to both hybrid buses and regular buses.

2.2.1 Fuel Economy Studies

This section summarizes previous studies about the fuel economy of hybrid buses and regular diesel buses. The percentage of improvements ranged from 5% to 30% depends on different scenarios. A summary of the findings are shown in table 2.4.

Table 2.4 Summary of fuel economy studies

Author	Bus Technology	Methodology	Major Findings
Northeast Advanced Vehicle Consortium (2000)	Hybrid bus, Regular bus, CNG	In-field test	The fuel economy of Allison hybrid bus was 3.1 mpg, while Orion hybrid bus was 2.7 mpg.
Federal Transit Administration (2000)	Hybrid buses	In-Field test	Hybrid buses improved 5% to 18% in fuel economy compared with regular diesel buses.
Zeng et al. (2005)	Hybrid bus, Regular bus	Dynamometer test & Simulation	Hybrid bus improved 30% in fuel economy compared with regular diesel bus.
Frey (2007)	Hybrid bus, Regular bus, Fuel Cell bus	Modeling	Vehicle specific power variable can be used to predict fuel economy.
Clark et al. (2009)	Hybrid bus, Regular bus, CNG bus	In-field test	In-filed fuel economies were ranged from 3.00 to 3.96 mpg at four study sites.
Liang et al. (2009)	Parallel Hybrid bus, Series Hybrid bus	In-field test	The fuel economy of parallel hybrid bus was 3.95 mpg, while series hybrid bus was 4.40 mpg.
Choi et al. (2010)	Plug-in hybrid bus, Electric-diesel hybrid bus	Dynamometer test	Plug-in hybrid electric bus reduced fuel consumption by approximately 40% ~ 50%.
Hallmark et al. (2010)	Plug-in hybrid school bus	In-field test	The fuel economy improvements were between 30 ~36 % for plug-in hybrid buses.

After hybrid bus technology became commercially available in late 1990s, the North Advanced Vehicle Consortium (2000) conducted one of the earliest studies in the U.S on evaluating fuel economy and emission levels of hybrid electric-diesel bus. They measured the in-field fuel economy for two hybrid buses. The in-use fuel economies for hybrid buses ranged from 2.7 mpg to 3.1 mpg based on different scenarios.

The Federal Transit Administration (2000) summarized the experience for New York, Cedar Rapids, and Los Angeles transit agencies. Each transit agency recorded their in-use fuel economy for both hybrid buses and regular buses. This study found the overall fuel economy improvements for hybrid buses were 18%, 15%, and 5% for New York, Cedar Rapids, and Los Angeles transit agency respectively. In addition, ancillary power unit and driver were also found to have a significant impact on fuel economy. In conclusion, the hybrid buses were reported to have better fuel efficiency, acceleration, and driving experience.

Zeng et al. (2005) conducted the only study to evaluate the fuel economy of hybrid transit buses using simulation software. The fuel economy of hybrid bus was tested by using dynamometer, whereas the fuel economy of conventional bus was simulated with the same engine load by using ADVISOR software. The simulation result showed 30% improvement in fuel economy of hybrid bus.

In recent years, several researchers used the vehicle specific power parameter to predict fuel consumption. Frey et al. (2007) developed a vehicle specific power modal approach to compare the buses with different propulsion systems. Twelve regular buses were tested in the city of Ann Arbor, while one regular diesel bus and one fuel cell bus was tested in Porto, Portugal. Portable Emission Monitoring System (PEMS) was used to collect emission data and instantaneous fuel consumption data. The Spearman correlation coefficients were used to check the correlation between fuel consumption and external factors. They found fuel type, speed, acceleration, and road grade were highly correlated to fuel consumption. In addition, passenger loading also had a significant effect on fuel consumption at middle or high speed. Fuel consumptions were stratified by VSP bins and found the fuel consumption rate increases monotonically with VSP bins.

The current development of hybrid bus technology was summarized by Clark et al. (2009) for four transit agencies, including New York, Seattle, Long Beach, and Washington, DC. Overall hybrid buses had in-field fuel economy between 3.00 mpg and 3.96 mpg. The dynamometer test showed the fuel economies of hybrid bus were between 4.2 mpg and 7.4 mpg. The dynamometer testing results for both hybrid buses and regular diesel buses are shown in table 2.5.

Table 2.5 Fuel economy and emissions test results on dynamometer

Bus Type	Manufacture	Test Cycle	Emission Rate (g/mile)					Fuel Economy
			CO	HC	NO_x	PM	CO_2	(mpg)
Diesel Hybrid	Gillig	CBD	1.4	0.03	13.9	0.019	1838	5.5
		OCTA	2.3	0.03	13.1	0.028	1716	5.9
		Manhattan	8	0.11	20.6	0.029	2401	4.2
		UDDS	1.9	0.04	9.1	0.033	1354	7.4
	Orion VII	CBD	0.08	0.11	12.9	0.012	1848	5.4
	Orion VII	CBD	0.15	0.02	9.1	0.022	1443	6.7
		OCTA	0.17	0.03	9.5	0.02	1640	5.9
		Manhattan	0.23	0.05	14.3	0.036	2000	4.8
		UDDS	0.1	0.03	8	0.018	1589	6.1
Conventional Diesel	Orion	CBD	1.4	0.05	25.4	0.17	2916	3.5
	Orion V	CBD	0.13	0.02	25.1	0.03	2958	3.4

Hallmark et al. (2010) evaluated in-use fuel economy of two plug-in hybrid school buses for two different school districts in Iowa. They recorded the odometer readings and amount of fuel used at fueling. In the Nevada school district, the average fuel economy was 9.12 mpg for the hybrid bus and 6.91 mpg for the control bus. In the Sigourney school district, the average fuel economy was 8.94 mpg for the hybrid bus and 6.42 mpg for the control bus. Bus route and driver were found to have significant impact on fuel economy.

Choi et al. (2010) conducted another study to use the vehicle specific power parameters to build fuel economy model and emission model. The testing buses were plug-in hybrid bus, diesel-electric hybrid bus, and conventional diesel bus. They used portable emission measurement system and on-board diagnostics (OBD) data logger to collect emission data as well as engine parameters. They built three models to estimate fuel economy. The best model, VSP model, predicted the fuel consumption reduction was between 40% and 50%. In addition, they also found the extra weight of battery pack on hybrid bus decreased fuel economy by 0.2 mpg on average.

2.2.2 Emissions Studies

Table 2.6 Summary of emission studies

Author	Bus Technology	Methodology	Major Findings
Shorter et al. (2005)	CNG, Hybrid bus, Regular bus.	Dynamometer test	Hybrid buses generated half of NO_x compared with regular buses.
Vikara et al. (2006)	Hybrid bus Regular bus	In-field test of ultrafine particle number distribution	The particle distribution was not different between diesel bus and hybrid bus.
Sonntag et al. (2008)	Hybrid bus, Regular bus	Modeling	Hybrid buses produced higher emission concentrations than the regular buses with statistical significance.
Zhai et al. (2008)	Regular Bus	In-field test	Increasing VSP was correlated to higher CO_2 and NO_x.
Mudgal (2009)	Regular bus with Bio-diesel fuels	In-field test	Emission rates were not proportional to percentage of biofuels.
Jackson et al. (2009)	Hybrid bus, Regular bus.	In-field test of particle number	Hybrid buses and regular diesel buses had no significant difference in particle number emissions.

This section summarizes previous studies that related to the emissions of hybrid buses and regular diesel buses. Most of emission data in those studies were collected by using

Portable Emission Monitoring Measurement System (PEMS). Although the hybrid buses are expected to generate less emission, most of studies found higher emission levels for hybrid buses. Only one studies (Shorter et al, 2005) found the hybrid bus generated half of NO_x than regular buses. A summary of the findings are shown in table 2.6.

Shorter et al. (2005) used an infrared laser spectrometer to measure the nitrogen oxygen emissions in real world driving conditions. 170 transit buses were selected in this study, including conventional diesel buses, diesel buses with continuously regenerating technology, electric-diesel hybrid buses, and compressed natural gas buses. The results showed the hybrid electric buses generated approximately half of the NO_x emissions than regular diesel buses.

Vikara et al. (2006) compared the ultrafine particle number distribution between hybrid buses and regular diesel buses using scanning mobility sampling technique. The three study routes were commuter bus freeway, arterial route, and suburban route. They found no difference in particle number distributions between diesel buses and hybrid buses on all three routes. This study also suggested route characteristics had a significant impact on particle number.

Sonntag et al. (2008) also conducted another study on the particle number of two hybrid buses and two regular diesel buses in 2004. Three routes were chosen to simulate different driving scenarios. This study used a linear mixed model to quantify the variability in the distribution of particle matters. They found the number of particle matters was correlated to bus route, driver, bus type, and daily temperature. The results showed the hybrid buses produced higher particle matter concentrations than regular buses with statistical significance.

Zhai et al. (2008) used portable emission monitoring system to collect real time emissions for 12 regular diesel buses. The collected emissions included carbon dioxide, hydrocarbon, carbon monoxide, and nitrogen oxides. They used the vehicle specific parameter to explain the variability of bus emissions. In general, increasing VSP was correlated to higher levels of carbon dioxide and nitrogen oxides. Additionally, the diesel fuel consumption rates were found to increase 33 percent when the number of passengers increased by 20.

Mudgal (2009) studied biodiesel emissions of regular diesel buses in Ames, Iowa. Mudgal used a Portable Emission Measurement System (PEMS) with an external GPS to measure emissions and other engine parameters. The on-board ridership was also counted manually. Three types of biofuels were tested, including regular diesel fuel, 10% biodiesel (B10), and 20% biodiesel (B20). The non-parametric method was used for statistical test. This study found no correlation between the percentage of ethanol in biodiesel fuels and the emission rates. Finally, emissions were found to increase monotonically with VSP bins.

Jackson (2009) examined particle number emission of hybrid buses and regular buses on three routes in Harford, Connecticut in 2004. They compared the VSP distributions between hybrid diesel buses and conventional diesel buses, but no difference were found between the two types of buses. The hybrid buses performed even worse in some cases.

2.2.3 Driving Behavior Studies

Table 2.7 Summary of driving behaviors studies

Author	Driving Behavior	Major Findings
Evans (1979)	Speed and trip time	Recommended to avoid stops, anticipate braking events, and use low acceleration levels to achieve better fuel economy.
Ericsson et al. (2000)	Route, driver, vehicle types	Street type and driver had the most significant impact on fuel economy and emissions.
Nam et al. (2002)	Aggressive driving	They found a strong relationship between aggressive driving and vehicle emissions.
Zorrofi et al. (2009)	Aggressive driving	Aggressive driving pattern had lower fuel economy than normal and mild driving patterns.
Sivak et al. (2011)	Impact of strategic decisions on fuel economy	They estimated that strategic decisions, tactical decisions, and operational decisions could reduce 45% in on-road fuel economy.
Mudgal (2011)	Driving behavior at traffic control devices	Driving behaviors were statistically significant at different traffic control devices.

This section summarizes previous driving behavior studies. Most of those studies were using passenger vehicles, instead of hybrid buses. They found more aggressive driving pattern usually correlated to higher fuel consumptions and emissions. A summary of the findings are shown in table 2.7.

Evans (1979) evaluated how driving behavior affects fuel consumption in urban driving environment. The data were collected based on 34 trips with nine different drivers. The vehicle was equipped with a fuel economy meter that had green, orange, and red regions. The drivers were told to follow several instructions for improving fuel economy, including:

1) Drive normally with the traffic;

2) Minimize trip time;

3) Use vigorous acceleration and deceleration;

4) Minimize fuel consumption;

5) Maintain fuel economy meter in green region;

6) Maintain fuel economy meter in orange region;

7) Behave as a very cautious driver.

Evans recommended improving fuel economy by adjust their driving behavior to avoid stops, anticipate braking events, and use low acceleration levels.

Ericsson (2000) studied the impact of vehicle type, traffic condition, and driver on the variability in fuel consumption and emissions. This paper used general factorial analysis of variance to study the variability among those factors. Ericsson found the street type has the largest impact on fuel economy, whereas the second largest source of variations came from the drivers. Besides, aggressive acceleration was found to be correlated with higher emissions.

Nam et al. (2002) measured vehicle emissions using the Portable Real-Time Emissions Vehicle Integrated Engineering Workstation (PREVIEW). In this study, the driver's aggressivity was defined as a function of speed and acceleration. They measured emissions with a Ford SUV in southeast Michigan. In conclusion, strong correlation was found between aggressive driving behavior and higher emissions.

Zorrofi et al. (2009) studied the impact of driving behaviors on fuel economy of hybrid transit buses by using computer simulations. The aggressive driving behavior was found to decrease the fuel economy significantly. The simulation results indicated the mild, normal, and aggressive driving pattern had fuel economy of 4.73, 4.32, and 1.76 mpg respectively.

Sivak (2011) evaluated different factors that could potentially impact the fuel economy of light-duty vehicles. The fuel economy improvement strategies were divided into three categories, including strategic decisions, tactical decisions, and operational decisions. The effects of those factors on fuel economy were summarized in table 2.8. The maximum reduction in fuel consumption was predicted to be 45%.

Table 2.8 Summary of the factors influencing vehicle fuel economy

Levels	Factor	Effect on Fuel Economy
Strategic	Vehicle class	38%
	Vehicle model	800% cars
	Vehicle configuration	18% cars
	Out-of-tune engine	4 - 40%
	Tires with 25% higher rolling resistance	3 - 5%
	Tires under inflated by 5 psi	1.50%
	Improper engine oil	1 - 2%
Tactical	Route type	variable
	Grade profile	15% - 20%
	Congestion	20% - 40%
	Extra 100 lbs. weight	<=2%
Operational	Idling	various
	Driving at high speeds	30%
	Not using cruise control	7%
	Using air conditioner	5 - 25%
	Aggressive driving	20 - 30%

Mudgal (2011) investigated the impact of driving behavior on emissions at three traffic control devices, including all-way stop, signalized intersection, and roundabout. The testing vehicle equipped with PEMS. The multivariate analysis of variance (MANOVA) model showed the driving behavior was statistically different at three traffic control devices, which were roundabout, stop controlled intersection, and signalized intersection. In the dissertation, Mudgal identified the gas pedal and brake pedal as two important indicators to explain the variability in vehicle emissions. In addition, Mudgal also suggest treating the driver factor as a random factor in driving behavior modeling.

2.3 Summary

This chapter summarizes previous studies that related to fuel economy, emissions, and driving behavior of hybrid bus. Several major findings from previous literatures are listed below.

1) Many researchers conducted both in-field measurements and dynamometer tests on the fuel economy of hybrid buses. The fuel economies improvements ranged from 5% to 30% improvements based on different scenarios. Other important findings that related to fuel economy are summarized below:

- Federal Transit Agency (2000). Ancillary power unit was found to have a great impact on fuel economy.
- Frey et al. (2007). The statistical test confirmed that fuel type, speed, acceleration, and road grade were highly correlated to the fuel consumption. In addition, passenger loading also had significant effect on fuel consumption.
- Hallmark et al. (2010). Bus route and driver were found to have significant impact on fuel economy.
- Choi et al. (2010). The extra weight of battery pack on hybrid bus decreased fuel economy by 0.2 mpg on average.

2) For emission studies, several researchers measured bus emissions using portable emission measurement system. No consistent conclusions were found about the emission reduction in hybrid buses. Some studies showed hybrid bus performed even worse in some cases. Other findings that related to hybrid buses are summarized below:

- Vikara (2006). Route characteristics were found to have significant impact on particle numbers.
- Sonntag et al. (2008). The distribution of particle matters was correlated to bus route, driver, bus type, daily temperature, and minor correlation with fuel types.
- Zhai et al. (2008). The diesel fuel consumption rates were found to increase by 33% when the number of passengers increased by 20.
- Mudgal (2009). No correlation was found between the percentage of ethanol in biodiesel fuels and the emission rates.

3) Only a few driving behavior studies were conducted in the past, and most of them were conducted on passenger vehicles. Based on those studies, driver, vehicle type, and road type were the three main factors to have significant impact on fuel economy and emissions. Some of the most important findings are summarized below:

- Evans (1979). It was recommended improving fuel economy by avoiding stops, anticipating braking events, and using low acceleration levels.
- Ericsson (2000). The street type was found to have the largest impact on fuel economy, whereas the second largest source of variance came from drivers. In addition, aggressive acceleration was found to be correlated to higher emissions.

- Mudgal (2011). The gas pedal and brake pedal position were identified as two important indicators to explain the variability in vehicle emissions.

Although many researchers studied hybrid buses, there are still some research gaps in this area. Most of the fuel economy studies were conducted before year 2006, and could not represent the fuel economy for the newest hybrid model. The drivers' driving behavior could have a direct impact on the fuel economy and emissions of hybrid buses, but none study had been conducted before. This thesis will focus on this area of study.

CHAPTER 3 EXPERIMENTAL DESIGN AND DATA QUALITY ASSURANCE

In chapter three, section 3.1 reviews the methodology to measure the real-time fuel economy. Section 3.2 presents the data collection and description of equipment in this experiment. Section 3.3 describes the procedures to reduce the data after data collection.

3.1 Fuel Economy Measurement Methodologies

Although the fuel economy consumption was not measured in this study due to some study limitations, it is still important to review the methodologies that used to measure the real-time fuel economy data. There are four main methods to measure the real-time fuel consumption.

3.1.1 Carbon Balance Measurement

Portable Emission Monitoring System (PEMS) consists of the main computer system, gas analyzer, global positioning system (GPS), emission sample lines, sensor array, and engine scanner. The emissions are sampled from the tailpipes and then analyzed in gas analyzer. The fuel consumption is calculated by equating the mass of carbon in the emissions to the carbon concentration in the fuels. The variables that used to calculate fuel economy include exhaust mass flow, emissions concentrations, and relative density. Several researchers used PEMS to measure the real-time fuel consumption. For example, Block et al. (2009) evaluated the fuel consumption of a tractor using portable emissions measurement system in Walker, Michigan. The fuel economy was proved to range from 7.515 mpg to 9.030 mpg.

Figure 3.1Axion Portable Emission Measurement System (PEMS)

3.1.2 Gravimetric Measurement

The common practice in SAE field to measure fuel economy is to use gravimetric measurements. The principal of gravimetric measurement is to measure the differences of the weights of the measuring vessel as an indicator for real-time fuel consumptions. For example, the AVL fuel balance measures the decreased weight of the measuring vessel through use of a capacitive sensor as shown in figure 3.2. The fuel consumption is usually reported in kg/h and g/s. The precision of the fuel consumption measurements are within 0.12% (±0.03g).

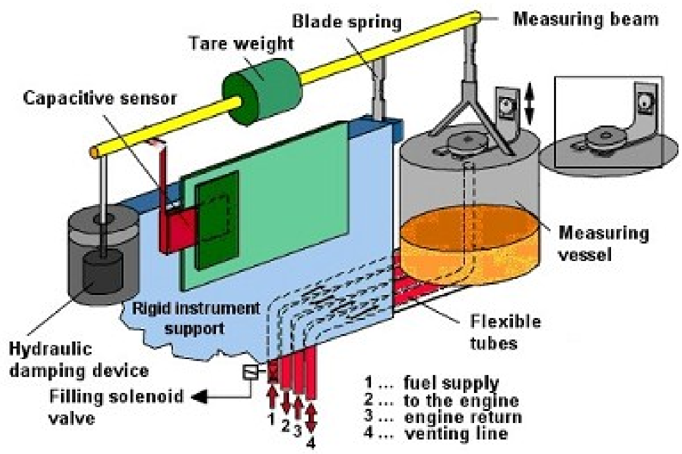


Figure 3.2 AVL fuel balance FlexFuel

Backman etc. (2006) compared the measurement between gravimetric measurements and portable emissions measurement system (PEMS) at Southwest Research Institute. They conducted 228 on-road tests on 8.5 miles oval track. The result showed the measurements from PEMS are highly correlated with gravimetric measurement results with a determination greater than 0.98. The findings supported the use of PEMS as a replacement for gravimetric method to measure fuel economy.

3.1.3 Engine Control Unit (ECU) Measurement

The fuel consumption can also be estimated based on the fueling demand signal, which indicates theoretical fuel consumption. The vehicle parameters were recorded from the electric control unit trough the on-board diagnostic system (OBD). The recorded variables include rpm, air filter, vehicle speed, and loading.

Liang et al. (2009) installed a data logger and GPS (Figure 3.3) on buses to compare the fuel economy of series hybrid bus and regular hybrid bus. The GPS data logger can read controller messages on vehicle, including vehicle speed, engine speed, engine torque, fuel consumption rate and other parameters.

Figure 3.3 Data taker DT80 and Gamin GPS 18 LVC

3.1.4 Volumetric Measurement

The volumetric measurement method is similar to gravimetric measurement. Instead of measuring the differences in fuel weights, the fuel flow meter measures the volume of fuels flow into the engine. Goncalves, G.A and Farias, T. L. (2007) measured the on-road emissions and fuel consumption of light duty vehicle in the Lisbon, Portugal. They developed the measurement system by integrating several different devices, including fuel flow meter, OBD interface, GPS, etc. The measured variables were topography, engine rpm, and instantaneous fuel consumption. However, they did not report the accurate of measurements.

3.2 Experimental Design

In order to test the impact of driving behavior on the fuel economy of hybrid buses, it is recommended to synchronize the fuel consumption data and the driving behavior data. However, due to various constraints, none of those four methods could be used in this study.

Therefore, the study focused on the GPS data only. A detailed description of the experiment is shown in the following sections.

3.2.1 Data Collection Protocol

After reviewed commercial GPS data loggers, six GPS data loggers were purchased and installed on three hybrid buses and three regular buses. GPS data were collected on ten weekdays from November 29 to December 12, 2011. CyRide had designated personnel to record fuel economy data every day. In general, the protocol of GPS data collection is shown below.

1) Each morning, CyRide lane workers placed the six GPS data loggers on the dashboards of testing buses as shown in figure 3.4.

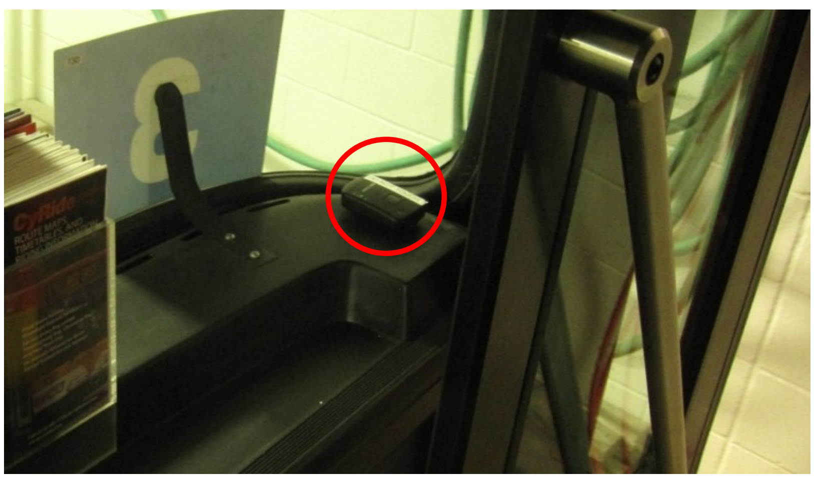


Figure 3.4 The GPS data logger was placed on the dashboard

2) The data loggers were recording the bus activities during the day. At the same time, the drivers also recorded the route number and counted the total number of

passengers for each trip.

3) After the buses came back to garage, the GPS data was downloaded using proprietary GPS data logger software (See figure 3.5).

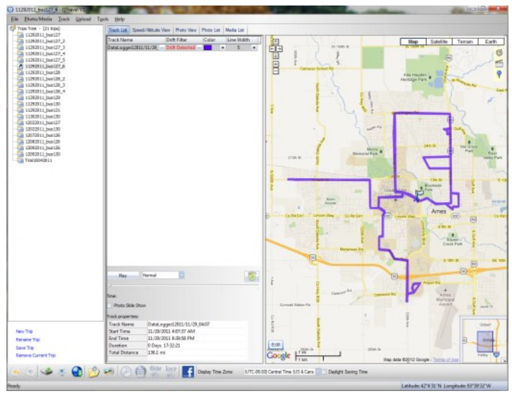


Figure 3.5 Screen shot of the software used to download GPS data

4) Upon completion of downloading, the memories of data loggers were erased so that enough memory space was available for the following day's data collection.
5) The data loggers would be charged overnight and the same data collection protocol continued for next day.

3.2.2 Description of CyRide Hybrid Buses and Conventional Buses

The testing parallel hybrid buses and regular diesel buses were produced from the same manufacture, Gillig. The capital cost of hybrid buses were 42% more expensive than regular buses. The diesel engines for both hybrid buses and regular diesel buses are the same, except that the hybrid buses have electric motors. CyRide hybrid buses are also weighed 4,500 lbs. heavier than regular buses due to the battery pack. Both hybrid and regular buses were equipped with diesel particular filters (DPF). Overall, the hybrid buses and regular diesel buses had very similar designs so that the results are comparable. Table 3.1 shows the comparison of specifications between hybrid buses and regular buses.

Table 3.1 Specifications for CyRide hybrid buses and regular diesel buses

	Hybrid Electric Diesel Buses	Regular Diesel Buses
Bus Number	129/130/131	126/127/128
Year	2010	2010
Capital Cost	Approximately $522,000	Approximately $367,000
Manufacture	Gillig electric-diesel hybrid	Gillig diesel
Bus Type	Low Floor	Low floor
Engine	Cummins '10 ISL 280 HP, in line six cylinders	Cummins '10 ISL 280 HP, in line six cylinders
Transmission	Voith DIWA parallel hybrid	Voith D864.5 4-speed
After-treatment	Particular filter	Particular filter
Governed Speed	65mph	65 mph
Start Date	6/28/2010	6/28/2010
Frontal Area	113.5 x 102 ft.	113.5 x 102 ft.
Dimensions	40 ft. x 138 in	40 ft. x 138 in
Curb Weight	29,500 lbs.	25,000 lbs.

Figure 3.6 CyRide hybrid bus

Photo Courtesy: CyRide Transit Agency

3.2.3 Modifications to the Hybrid Buses

The CyRide hybrid buses were pre-production buses, which means the bus manufacture would use those buses to detect any problems before they are commercially available. Therefore, the CyRide hybrid buses were not in its optimum conditions and several tweaks were made during the study period. The most frequent modifications to the hybrid buses were fixing the braking pedals. Besides, Gillig also installed new programs on hybrid buses for fuel economy improvement. In summary, the major tweaking events recorded in this study are shown in table 3.2.

Table 3.2 Bus tweaks and time

Time	Tweak Events
22-Jun-2011	Fixed electronic brake pedals on 2 buses
5-Jul-2011	Fixed electronic brake pedals on 2 buses
15-Jul-2011	Fixed rest of brake pedals and installed new programming for all buses
12-Sep-2011	Fixed all braking pedals on all buses
9-Dec-2011	Replaced 2 software programs, changed the shifting routing on 8 buses, changed braking pedal on 4 buses
30-Dec-2011	Fixed braking pedal and changed software programming
10-Feb-2012	Minor changes for transmission

3.2.4 CyRide Transit System

CyRide operated 12 fixed routes in fall 2011 and most routes ran through ISU campus. The CyRide hybrid buses and regular buses were rotated on different routes due to the economic inequality concerns. However, the rotation of buses resulted in less efficient experiment design for this study since unwanted routes had to be recorded during this study. All CyRide bus routes operated on either two-lane or four-lane paved roads with speed limits ranged from 25 mph to 45 mph. The following map shows the CyRide transit system in fall 2011.

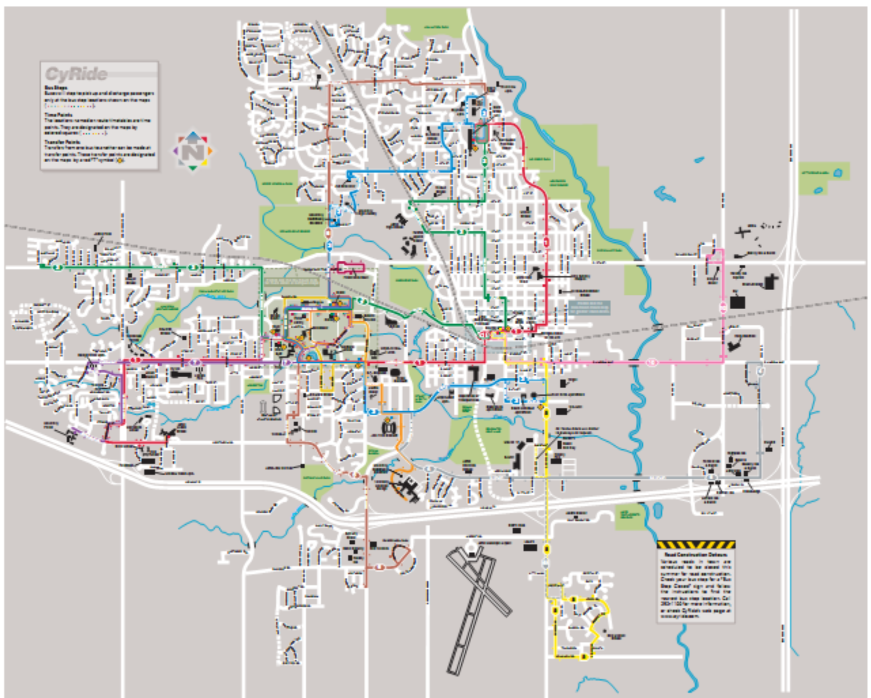


Figure 3.7 CyRide bus routes in fall 2011

Source: CyRide, 2012

3.2.5 GPS Data Loggers

Several commercial GPS data loggers were compared based on its prices, accuracy, memory space, and battery life. Finally, the CP-Q 1100 P data loggers were chosen to collect vehicle activity data. The data loggers had 40 hours battery life, memory up to 400,000 records, and excellent GPS accuracy. The GPS data loggers were placed on the dashboard of testing buses during data collection. The frequency of data collection could be up to 5 Hz, but the data loggers were set to record data at every second in this study.

Figure 3.8 CP-Q1100P GPS tracking recorder

Source: QSTARZ, User's Manual

3.2.6 Weather Conditions

Weather conditions could have a great impact on the driving behavior. In order to make the results comparable, the weather conditions should be similar. The weather information was retrieved through the Wunderground website (http://www.wunderground.com/). In summary, the weather conditions were mostly clear or partly cloudy during the study period. Therefore, the weather conditions were assumed to have negligible impact in this study.

3.2.7 Fuel Types

CyRide used biodiesel fuels with 2% ethanol blend consistently throughout this study. Buses using other types of fuels may have different fuel economy results and driving performance than this study.

3.2.8 Route Selection

More than six hundreds of bus routes and 65 drivers were recorded during this study period, but had low repeatability. Since we want to minimize the interference to the daily operation of transit agency, several external factors could not be controlled in this study, including drivers' work schedule, bus rotation, and route pattern. This resulted in very low efficient experimental design. Two routes were chosen to represent the two typical roadway environments in the city of Ames, including arterial route and campus route.

1) *Arterial route*. Arterial route represented the arterial driving environment in the city of Ames. The length of arterial route was three miles on Lincoln way (figure 3.9). It was a paved four-lane divided road with speed limit at 30 mph. This route contains eight intersections. The annual average daily traffic was from 13,500 to 23,600 based on the 2007 traffic data (Iowa DOT).

Figure 3.9 Arterial route includes eight intersections on Lincoln Way

2) *Campus route*. The campus route ran through Iowa State University campus, where has little through traffic but heavy pedestrian activities. The length of the campus route was 0.77 miles and contains seven stops. The roads were paved two lanes with speed limits at 25 mph, but buses usually drove much slower due to frequent stops.

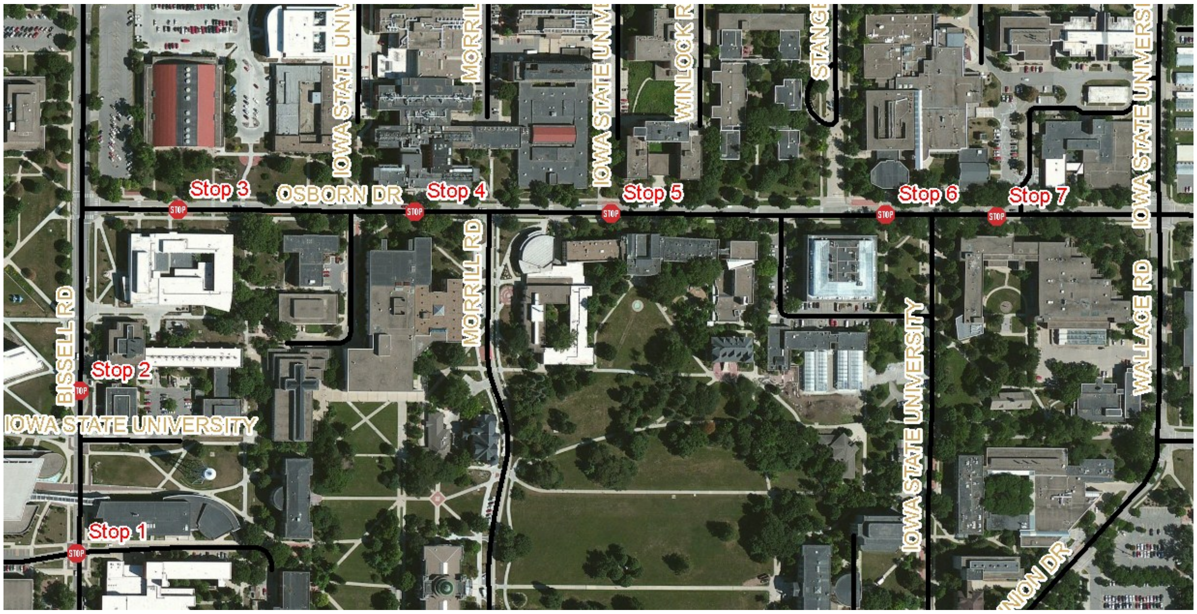


Figure 3.10 Campus route includes seven stops on Osborn Dr.

3.2.9 Drivers

Since the drivers' work schedules were predetermined before the data collection, the driver factor could not be controlled in this experiment. As a result, 65 drivers were recorded during the ten day's GPS data collection. However, not many drivers drove both hybrid buses and regular buses on the same route. After the dataset were reduced, only six drivers were included in the final statistical analysis.

2.2.10 Summary of the Collected Raw Data

During a typical day, a data logger recorded approximately 60,000 rows of observations for each bus. A total of 3 million observations were recorded during this study. The descriptions of the collected raw data are listed in table 3.3. The variables that included in this study were date/time, latitude, longitude, speed, PDOP, and NSAT.

Table 3.3 The collected GPS raw data variables

Format Type	Item	Description
Universal Time Clock	Date/Time	Universal Coordinated Time.
Navigation	Latitude	A north/south measurement of position perpendicular to the earth's polar axis.
	Longitude	An east/west measurement of position in relation to the Prime Meridian, an imaginary circle that passes through th e north and south poles.
	height	The altitude of a place above sea level or ground level.
	Speed	Rate of motion.
	Heading	The compass direction in which the longitudinal axis of a ship or aircraft points.
Dilution of Precision	PDOP	(Positional Dilution Of Precision); Position accuracy; 3D coordinates.
	HDOP	(Horizontal Dilution Of Precision); horizontal accuracy; 2 D coordinates.
	VDOP	(Vertical Dilution Of Precision); vertical accuracy; height.
Satellite Information	NSAT	Number of Satellite (in Used, in View).
Other	Distance	The distance between two logging points.

Source: QSTARZ, User's Manual.

3.3 Data Post-Processing

After the raw GPS data were collected, post-processing procedures were conducted to prepare the final dataset. Data post-processing is a process that transforms the collected raw data into an organized, corrected, and simple form that can be used later for data analysis. There are eight steps in the data post-processing procedures. First of all, the GPS data needs to be validated. Second, the vehicle specific power (VSP) formulas were created for CyRide buses. After that, several driving behavior variables were created in step three. Fourth, the GPS data were integrated with trip information. Fifth, the data were imported into GIS based on its coordinates. Sixth, the data near intersections were extracted. Seventh, the data were summarized at each intersection. Finally, all trips that did not stop at intersections were excluded from the final dataset. The flow chart of the nine steps is shown in figure 3.11.

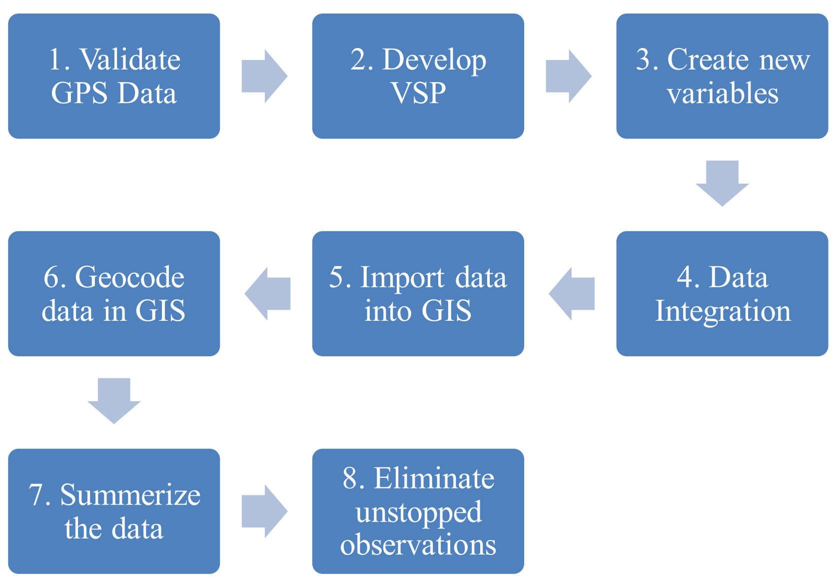


Figure 3.11 Eight steps for data reduction and quality assurance

3.3.1 GPS Data Validation

The first step was to ensure the collected GPS data were valid. GPS data loggers had been used by many researchers to measure vehicle activities. Belliss (2004) evaluated the accuracy of several commercial GPS data loggers and found the accuracy of speeds was within ±0.12 mph, while the accuracy of acceleration was within ±0.22mph/s. Ogle et al. (2002) summarized sources of errors from GPS data, including satellite orbit error, satellite clock error, receiver error, etc. Three methods were proposed to check the quality of GPS data.

1) *Check the Position Dilution of Precision (PDOP) value*. PDOP value greater than four indicates poor satellite geometry, and those observations should be excluded from the dataset.

2) *Check the number of satellites*. Three satellites are required to provide accurate coordinate data, but four satellites are recommended.

3) *Inspect roadway environment visually*. GPS data can be blocked by tall buildings in urban canyon. The quality of GPS signals can be checked by visual inspection of roadway environment.

In this study, all GPS data loggers received signals from at least four satellites at all time. Besides, Ames did not have any urban canyon environment, so all GPS data were kept in this study.

3.3.2 Development of VSP Formula

This section introduces the methodology to develop vehicle specific power parameter for CyRide buses. Vehicle specific power is a ratio of instantaneous vehicle power over vehicle mass. Jimenez-Palacios (1993) summarized the three main reasons to use VSP to estimate vehicle performance. First, VSP parameter can capture the most dependent variables that related to the fuel economy and emissions, including rolling resistance, aerodynamic drag, kinetic energy, and potential energy of the vehicle. Second, VSP can be easily measured and calculated from roadside measurements. Third, VSP is directly specified in emission certification cycles.

Several studies have been conducted to use VSP to explain the variability within emissions and fuel consumption. Frey (2007) tested 12 hybrid buses found the emissions increase with VSP as shown in figure 3.12. Zhai (2008) and Mudgal (2009) found increasing VSP resulted in higher levels of CO_2 and NO_x. Jackson (2009) found the VSP distribution is similar between hybrid buses and regular buses.

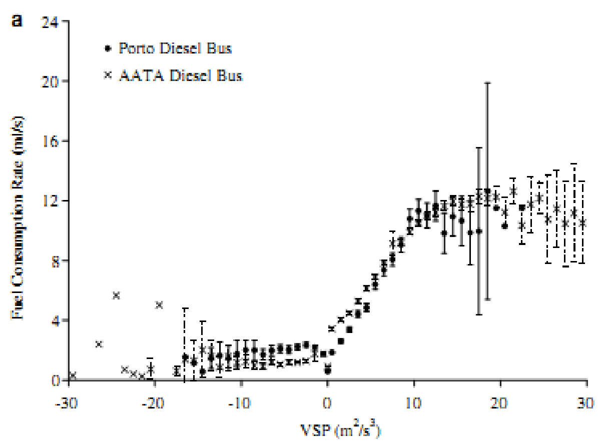


Figure 3.12 Fuel consumption rate by VSP mode

Source: Frey et al, 2007.

Since hybrid buses and diesel buses have different weights, two different VSP formulas were developed for CyRide hybrid buses and regular diesel buses. Based on several assumptions, the developed formula is a function of speed and acceleration as shown in formula (1) and formula (2). Both formulas assumed the average value for rolling resistance coefficient ($C_R * g * V$) and the aerodynamic drag term coefficient ($C_D * \frac{A}{m}$). In addition, the value of air density ρ is assumed to be the standard air density at 68°F (20°C). All parameters shown in formula 1 and 2 are specified in table 3.4.

Table 3.4 The parameters that specified in formula 1 and formula 2

Parameters	Explanation	Value
VSP	Vehicle Specific Power (kW/Metric Tons = W/kg = m^2/s^3=0.1998 mph^2/s)	Calculated (mph^2/s)
ε	Equivalent translational mass of the rotating components of the powertrain. (dimensionless)	0.1
v	Vehicle speed, mph	Measured
a	Vehicle acceleration, mph/s	Measured
grade	Slope length	0, assume to be flat
g	Acceleration of gravity, m/s^2	Mph^29.8
C_R	Coefficient of rolling resistance (dimensionless)	0.01
C_D	Drag coefficient (dimensionless)	0.5
A	Frontal area of the vehicle, m^2	7.47
ρ	Ambient air density kg/m^3, at 20 °C	1.207
v_w	Headwind into the vehicle, mph/s	Negligible

VSP Formula for Regular Bus:

$$\mathrm{VSP} = \left(\frac{d}{dt}(\text{Kinetic Energy} + \text{Potential Energy}) + F_{\text{rolling}} * V + F_{\text{Aerodynamic}} * V\right)/m$$

$$= \frac{d}{dt}\left(\frac{1}{2}(1+\varepsilon_i)V^2 + gh\right) + C_R * g * V + \frac{1}{2}\rho\frac{C_D A}{m}(v+v_w)^2 v$$

$$= V(a(1+\varepsilon_i) + g \cdot \text{grade} + C_R * g) + \frac{1}{2}\rho\frac{C_D A}{m}(v+v_w)^2 v$$

$$= V(1.1 \cdot a + 0.22) + 0.00008886v^3 \qquad \textit{(formula 1)}$$

VSP Formula for Hybrid Bus:

$$\text{VSP} = \left(\frac{d}{dt}(\text{Kinetic Energy} + \text{Potential Energy}) + F_{\text{rolling}} * V + F_{\text{Aerodynamic}} * V\right)/m$$

$$= \frac{d}{dt}\left(\frac{1}{2}(1+\varepsilon_i)V^2 + gh\right) + C_R * g * V + \frac{1}{2}\rho\frac{C_D A}{m}(v+v_w)^2 v$$

$$= V(a(1+\varepsilon_i) + g \cdot \text{grade} + C_R * g) + \frac{1}{2}\rho\frac{C_D A}{m}(v+v_w)^2 v$$

$$= V(1.1 \cdot a + 0.22) + 0.0000753v^3 \qquad \textit{(formula 2)}$$

3.3.3 Create Driving Behavior Variables

Several new variables were created to characterize the driving behavior. Acceleration was calculated from the measured speed. Deceleration was created separately with acceleration. The vehicle specific power was a function of speed and acceleration. Positive kinetic energy (PKE) was the sum of all positive vehicle specific power values, while negative kinetic energy (NKE) was the sum of all negative vehicle specific power values. Idling was defined as speed less than 1 mph. The cruise variable was defined when speed differential between two consecutive seconds was less than 1 mph. A list of created variables and descriptions are shown in table 3.5 on next page. It should be noted that the conversion factor for acceleration is 1 mph/s = 0.447 m/s^2.

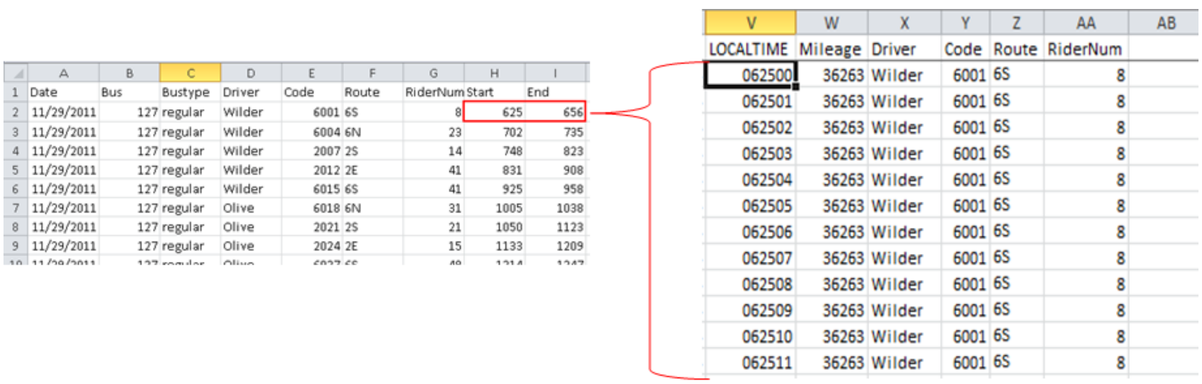
Table 3.5 The created variables in the final dataset

Variables	Description	Derivation	Unit
Moving Speed	Moving speed	Speeds larger than 1 mph	mph
ACC	Acceleration	acceleration = d(speed)/dt, for ACCi >0	mph/s
MAX ACC	Maximum acceleration	MAXACC=max(ACCi), for all ACCi>0	
STD ACC	Standard deviation acceleration	STDACC=std(ACCi), for all ACCi>0	
DEC	Deceleration	Deceleration = d(speed)/dt, for DECi <0	mph/s
MAX DEC	Maximum deceleration	MAXDEC=max(DECi), for all DECi>0	
STD DEC	Standard deviation of deceleration	STDDEC=std(DECi), for all DECi>0	
VSP	Average VSP	VSP = V(1.1·a+0.22)+0.00008886v^3, for hybrid bus	mph2/s
PKE	Positive kinetic energy	PKE=SUM(VSP_i), for VSP_i >0	mph2/s
NKE	Negative kinetic energy	NKE=SUM(VSP_i), for VSP_i <0	mph2/s
Idling	Percentage of time in idling mode	Idling=(time with speed less than 1 mph)/(Total Time)	%
Cruise	Percentage of time in cruise mode	Cruise=(time with constant speed larger than 1 mph)/(Total Time)	%
ACC1	Distribution of time in acceleration interval between 0 mph/s to 1 mph/s	$ACC1 = \frac{Time\ in\ interval\ between\ 0\frac{mpg}{s}to\ 1\ mph/s}{Total\ Time}$	%
ACC2	Distribution of time in acceleration interval between 1 mph/s to 2 mph/s	$ACC2 = \frac{Time\ in\ interval\ between\ 1\frac{mpg}{s}to\ 2\ mph/s}{Total\ Time}$	%
ACC3	Distribution of time in acceleration interval larger than 2 mph/s	$ACC3 = \frac{Time\ in\ interval\ larger\ than\ 2\ mph/s}{Total\ Time}$	%
DEC1	Distribution of time in deceleration interval between 0 mph/s to -1 mph/s	$ACC1 = \frac{Time\ in\ interval\ between\ 0\frac{mpg}{s}to\ 1\ mph/s}{Total\ Time}$	%
DEC2	Distribution of time in deceleration interval between -1 mph/s to -2 mph/s	$ACC2 = \frac{Time\ in\ interval\ between\ 1\frac{mpg}{s}to\ 2\ mph/s}{Total\ Time}$	%

DEC3	Distribution of time in deceleration interval larger than -2 mph/s	$ACC3 = \frac{Time\ in\ interval\ larger\ than\ 2\ mph/s}{Total\ Time}$	%

3.3.4 Data Integration

The final dataset combined data from two sources, which include GPS data and trip information. Trip information contains driver name, bus type, total number of passengers, and bus route for the trip. The trip information was copied to GPS data by time stamp. For example, the figure 3.14 shows the trip information on the left is copied to the GPS dataset on the right.



	A	B	C	D	E	F	G	H	I
1	Date	Bus	Bustype	Driver	Code	Route	RiderNum	Start	End
2	11/29/2011	127	regular	Wilder	6001	6S	8	625	656
3	11/29/2011	127	regular	Wilder	6004	6N	23	702	735
4	11/29/2011	127	regular	Wilder	2007	2S	14	748	823
5	11/29/2011	127	regular	Wilder	2012	2E	41	831	908
6	11/29/2011	127	regular	Wilder	6015	6S	41	925	958
7	11/29/2011	127	regular	Olive	6018	6N	31	1005	1038
8	11/29/2011	127	regular	Olive	2021	2S	21	1050	1123
9	11/29/2011	127	regular	Olive	2024	2E	15	1133	1209

V	W	X	Y	Z	AA	AB
LOCALTIME	Mileage	Driver	Code	Route	RiderNum	
062500	36263	Wilder	6001	6S	8	
062501	36263	Wilder	6001	6S	8	
062502	36263	Wilder	6001	6S	8	
062503	36263	Wilder	6001	6S	8	
062504	36263	Wilder	6001	6S	8	
062505	36263	Wilder	6001	6S	8	
062506	36263	Wilder	6001	6S	8	
062507	36263	Wilder	6001	6S	8	
062508	36263	Wilder	6001	6S	8	
062509	36263	Wilder	6001	6S	8	
062510	36263	Wilder	6001	6S	8	
062511	36263	Wilder	6001	6S	8	

Figure 3.13 Use time stamp to attach trip information to GPS data

3.3.5 Import Data into GIS

Although the buses were supposed to run as scheduled route pattern, some unexpected trips might occur during trips, which should be excluded from data analysis. Therefore, the GPS data were inspected visually in Geographic Information System (GIS). For example, the highlighted link in figure 3.14 shows the bus stopped in the middle of the Red route and drove back to garage. Thus, this trip was excluded from final data analysis.

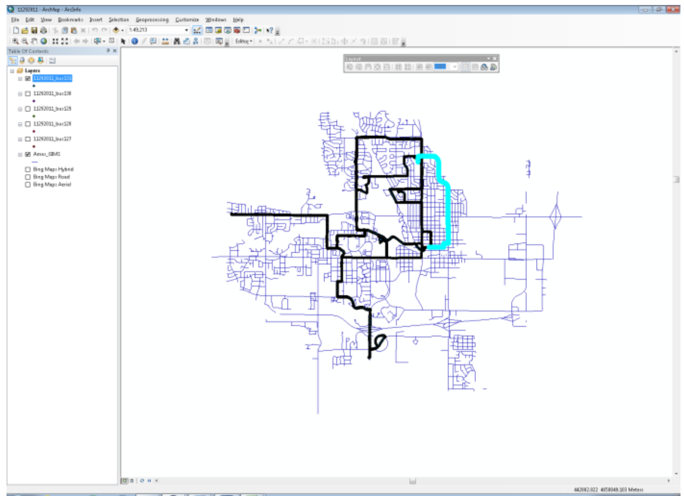


Figure 3.14 The Red Southwest trip was eliminated on Nov 29, 2011

3.3.6 Geocode Data in GIS

In order to analyze the driving behavior near intersections, the radius of influence for intersections is defined in this study. For arterial route, 300 feet radius was used to define the influence of the intersection. Therefore, the data within 300 feet radius were exported from GIS as shown in figure 3.15. Similarly, the radius of influence was assumed to be 150 feet on campus route due to the lower driving speed.

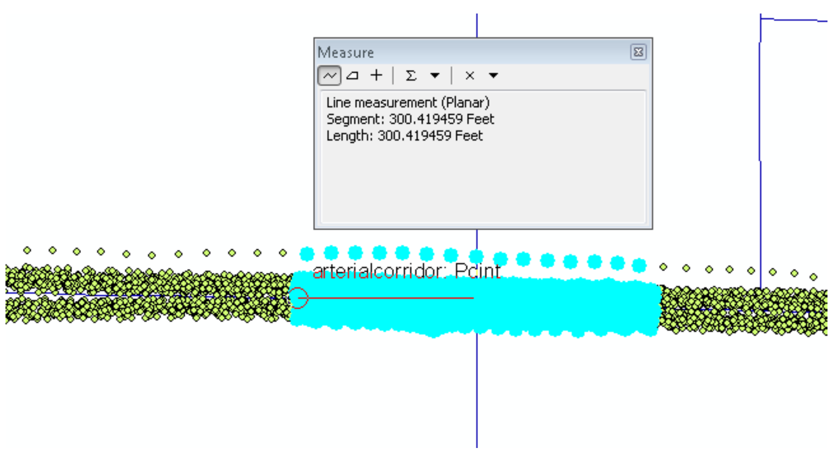


Figure 3.15 GPS data points within 300 feet are selected on arterial route

3.3.7 Calculate the Mean Values

By this step, the data were still in second-by-second format. Since the analysis would be performed at intersection level, the averaged values were calculated for each intersection.

3.3.8 Eliminate Unstopped Observations

Since the focus of this study is to test the deceleration and acceleration behavior, only the observations that stopped at intersections were kept in the dataset. If a bus did not stop at the intersections, the observations would not be comparable with those stopped observations. Therefore, the non-stopped observations were deleted from the dataset. The unstopped observations were defined by using the criteria that minimum speed at intersections is larger than 2 mph.

After those eight steps, the final dataset is prepared so that it could be analyzed later in exploratory analysis and full statistical analysis in chapter four.

CHAPTER 4 DRIVING BEHAVIOR ANALYSIS

This chapter first investigated the driving behavior parameters by using exploratory analysis so that we could have a general idea about how the data were distributed. However, the exploratory analysis is only observational and the findings should be tested by using statistical analysis. The analysis of variance (ANOVA) was proposed to test the statistical significance, but the normality assumption was grossly violated. Instead, the nonparametric method was used to conduct the statistical test. In addition, regression models were also built to analyze the same dataset from different perspective. Finally, the results are compared between nonparametric statistical test and regression model.

4.1 Exploratory Analysis

4.1.1 Descriptive Statistics

Fifteen variables were used to characterize driving behavior. Those variables were then divided into three categories, which are level variables, power demanding variables, and distribution variables as shown in Table 4.1. Level variables indicate the basic operating parameters of the buses, including moving speed, acceleration, and deceleration. Power demanding variables summarize the external loading of the buses. Time distribution variables show the time distribution within different acceleration and deceleration intervals. For example, more time spent in higher acceleration interval means more aggressive accelerating behavior.

Table 4.1 Three categories of driving behavior variables

Level Variables (L)	Power Demanding Variables (E)	Time Distribution Variables (T)
Moving Speed	Positive Kinetic Energy	% of Time in acceleration intervals between 0 mph/s and 1 mph/s
Average Acceleration	Negative Kinetic Energy	% of Time in acceleration intervals between 1 mph/s and 2 mph/s
Maximum Acceleration		% of Time in acceleration intervals larger than 2 mph/s
Std. Dev. Of Acceleration		% of Time in deceleration intervals between 0 mph/s and -1 mph/s
Average Deceleration		% of Time in deceleration intervals between -1 mph/s and -2 mph/s
Maximum Deceleration		% of Time in deceleration intervals less than -2 mph/s
Std. Dev. Of Deceleration		

Table 4.2 and 4.3 present the descriptive statistics for all variables on arterial route and campus route. The descriptive statistics include mean, standard deviation, skewness, and kurtosis. Skewness indicates the amount and direction of skew. Negative skew usually indicates the tail is longer on the left side, while positive skew indicates the tail is longer on the right side. Kurtosis number quantifies the sharpness and height of the central peak. Both skewness and kurtosis number should be within ±3. The descriptive statistics found six variables on arterial route and five variables on campus route have high Kurtosis numbers. Those variables with high Kurtosis numbers should be treated with transformation technique.

Table 4.2 Descriptive statistics for driving parameters on arterial route

	Parameters	Mean	Max.	Min.	Std. Dev.	Skewness	Kurtosis	# of Obs.
Arterial Regular	Moving Speed	16.411	21.810	11.637	2.360	-0.055	-0.749	120
	Acceleration	1.783	2.477	1.220	0.269	0.131	-0.343	120
	Max ACC	4.331	10.340	2.215	1.665	1.972	3.623	120
	Std. ACC	1.118	2.139	0.551	0.267	0.971	1.831	120
	Deceleration	-1.748	-1.076	-3.147	0.418	-0.655	0.249	120
	Max DEC	-4.522	-1.970	-18.474	2.744	-3.456	12.669	120
	Std. DEC	1.244	4.110	0.561	0.600	2.892	9.949	120
	PKE	559.282	1228.38	243.975	195.284	1.305	1.783	120
	NKE	- 498.482	- 217.900	- 931.580	194.036	-0.796	-0.457	120
	ACC1	0.139	0.400	0.000	0.082	0.803	0.540	120
	ACC2	0.170	0.350	0.025	0.070	0.266	0.189	120
	ACC3	0.197	0.450	0.075	0.085	1.174	0.952	120
	DEC1	0.193	0.525	0	0.115	0.733	-0.022	120
	DEC2	0.160	0.575	0.000	0.115	1.221	1.753	120
	DEC3	0.185	0.4	0	0.079	0.690	0.563	120
Arterial Hybrid	Moving Speed	16.633	21.582	8.175	2.418	-0.629	0.613	120
	Acceleration	1.670	2.493	0.939	0.267	0.667	1.078	120
	Max ACC	4.388	14.677	1.920	2.189	2.592	7.770	120
	Std. ACC	1.141	3.791	0.373	0.434	2.790	13.463	120
	Deceleration	-1.665	-0.846	-2.758	0.398	-0.480	0.248	120
	Max DEC	-3.828	-2.434	-9.947	1.245	-2.363	8.700	120
	Std. DEC	1.110	2.562	0.615	0.357	1.294	2.915	120
	PKE	515.505	995.862	248.617	144.350	0.689	1.578	120
	NKE	- 440.589	-190.04	-1022	149.664	-1.513	3.256	120
	ACC1	0.159	0.475	0.025	0.084	1.121	1.419	120
	ACC2	0.167	0.450	0.025	0.083	0.809	0.723	120
	ACC3	0.172	0.375	0	0.074	0.813	1.026	120
	DEC1	0.199	0.975	0.025	0.141	2.205	7.648	120
	DEC2	0.147	0.200	0	0.103	1.532	3.335	120
	DEC3	0.174	0.450	0.075	0.065	1.525	4.729	120

Table 4.3 Descriptive statistics for driving parameters on campus route

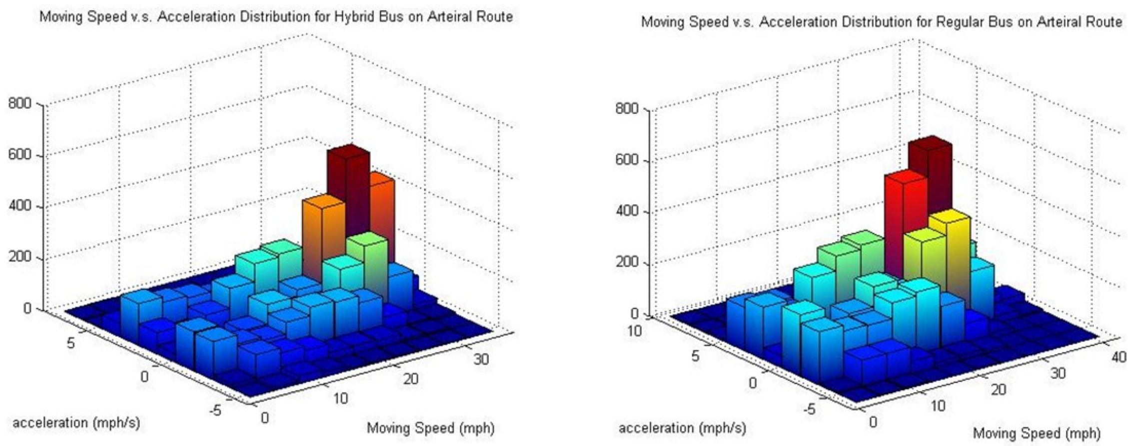
	Parameters	Mean	Max.	Min.	Std. Dev.	Skewness	Kurtosis	# of Obs.
Campus Regular	**Moving Speed**	9.632	13.470	5.438	1.894	-0.060	-0.791	120
	Acceleration	1.710	3.120	0.833	0.469	0.794	0.661	120
	Max ACC	4.191	10.951	1.498	1.773	1.600	2.705	120
	Std. ACC	1.266	3.222	0.383	0.487	1.362	2.713	120
	Deceleration	-1.500	-0.654	-3.505	0.416	-1.427	4.628	120
	Max DEC	-3.865	-1.457	-14.114	1.964	-2.238	6.504	120
	Std. DEC	1.109	3.862	0.426	0.486	2.270	8.529	120
	PKE	187.234	368.248	44.723	69.722	0.463	-0.018	120
	NKE	-193.887	-37.541	-474.28	89.349	-0.814	0.556	120
	ACC1	0.118	0.268	0	0.066	0.498	-0.534	120
	ACC2	0.083	0.195	0	0.046	0.371	-0.141	120
	ACC3	0.106	0.268	0	0.052	0.429	0.502	120
	DEC1	0.142	0.489	0	0.079	1.434	3.279	120
	DEC2	0.109	0.268	0	0.051	0.534	0.365	120
	DEC3	0.095	0.244	0	0.050	0.386	-0.210	120
Campus Hybrid	**Moving Speed**	9.417	12.444	4.777	1.624	-0.431	-0.345	120
	Acceleration	1.589	2.525	0.628	0.396	0.068	-0.223	120
	Max ACC	3.770	10.52	1.487	1.511	1.591	3.163	120
	Std. ACC	1.094	2.576	0.378	0.396	1.286	2.083	120
	Deceleration	-1.378	-0.695	-2.966	0.343	-0.874	2.771	120
	Max DEC	-3.426	-1.106	-13.856	1.351	-4.191	29.430	120
	Std. DEC	1.051	3.792	0.321	0.365	3.732	26.973	120
	PKE	145.603	409.445	21.994	88.919	0.890	0.418	120
	NKE	-66.911	-0.225	-334.360	69.193	-1.486	2.578	120
	ACC1	0.125	0.512	0.024	0.082	1.540	3.963	120
	ACC2	0.093	0.341	0.024	0.053	1.245	3.093	120
	ACC3	0.106	0.2439	0.000	0.054	0.107	-0.161	120
	DEC1	0.168	0.341	0.024	0.073	0.319	-0.360	120
	DEC2	0.108	0.244	0	0.056	0.437	-0.301	120
	DEC3	0.089	0.220	0	0.043	0.190	0.326	120

4.1.2 Exploratory Analysis of Driving Behavior Parameters

Before the full statistical analysis of driving behavior, this section visually investigated the driving behavior variables to get a general idea of how the variables were distributed. This information is useful to help us decide which variables to be included in the full statistical test.

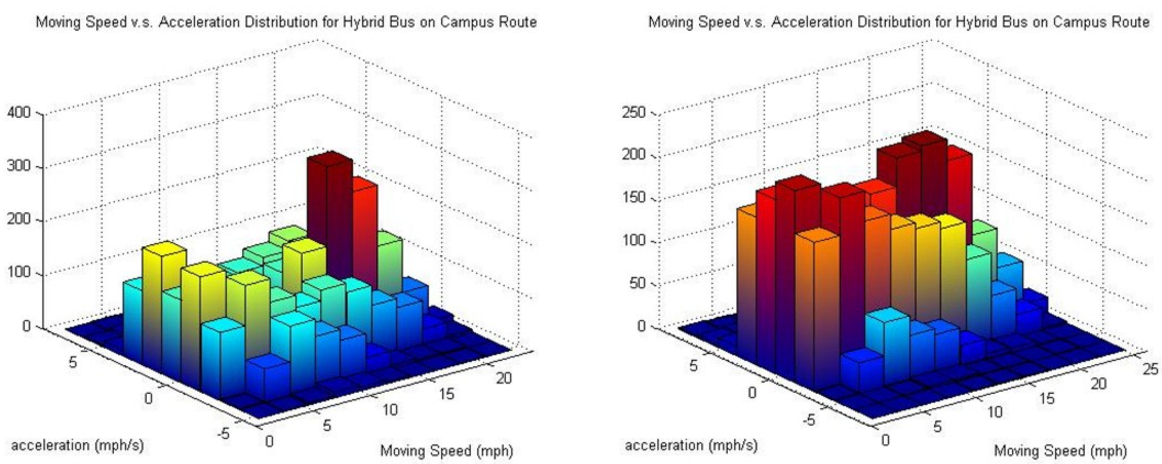
4.1.2.1 Moving Speed and Acceleration Distribution

Moving speed and acceleration are the two most important variables that used to characterize vehicle activities. The figure 4.1 and figure 4.2 plotted the histogram of acceleration (mph/s) versus moving speed (mph) for both hybrid buses and regular buses. Moving speed includes all speeds over 1 mph, which means the idling mode was excluded from the charts. Figure 4.1 compares the driving behavior for hybrid buses and regular buses on arterial route. Based on the figure, a peak frequency was found at speeds interval between 20 and 30 mph, and the acceleration interval between -2 mph/s and 2 mph/s. This area is shown in brighter colors in figure 4.1. On the other hand, if the figure 4.1 was compared with figure 4.2, the distributions were different between the two routes. For example, the peak frequency on campus route was not found as obvious as arterial route's. Therefore, the driving behavior was similar between hybrid buses and regular buses, but was different on two routes.



Hybrid Buses Regular Buses

Figure 4.1 Moving speed and acceleration distribution on arterial route



Hybrid Buses Regular Buses

Figure 4.2 Moving speed and acceleration distribution on campus route

4.1.2.2 Speed Profile by Drivers

The speed profiles by drivers are averaged over 240 trips. The figure 4.3 plotted the speed profiles on arterial route, while figure 4.4 plots the speed profiles on campus route. One of most important findings was that drivers brought a large variability in speed profiles as indicated in red circles in figure 4.3 and figure 4.4. Therefore, the driver variable was recommended to be included in the statistical analysis.

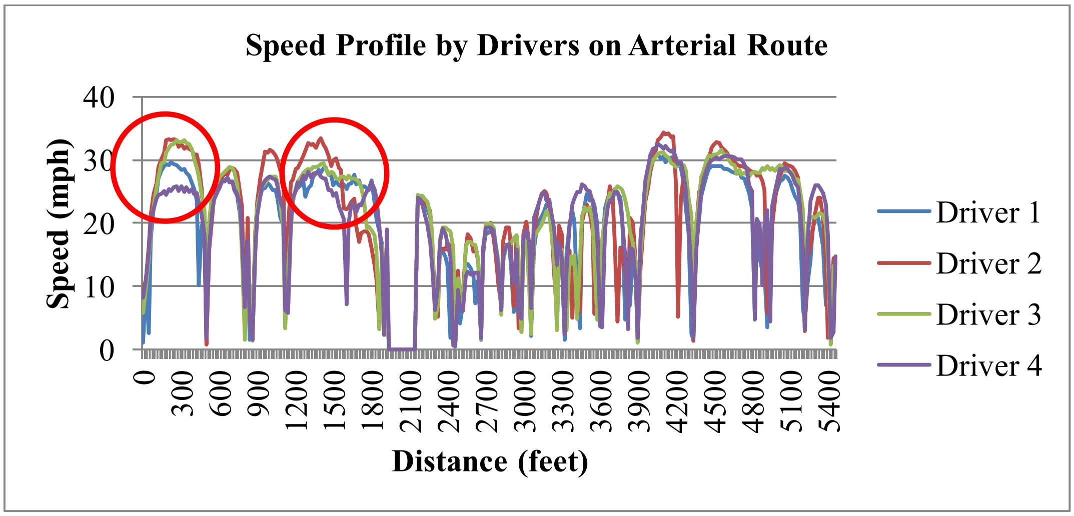


Figure 4.3 Speed profiles by drivers on arterial route

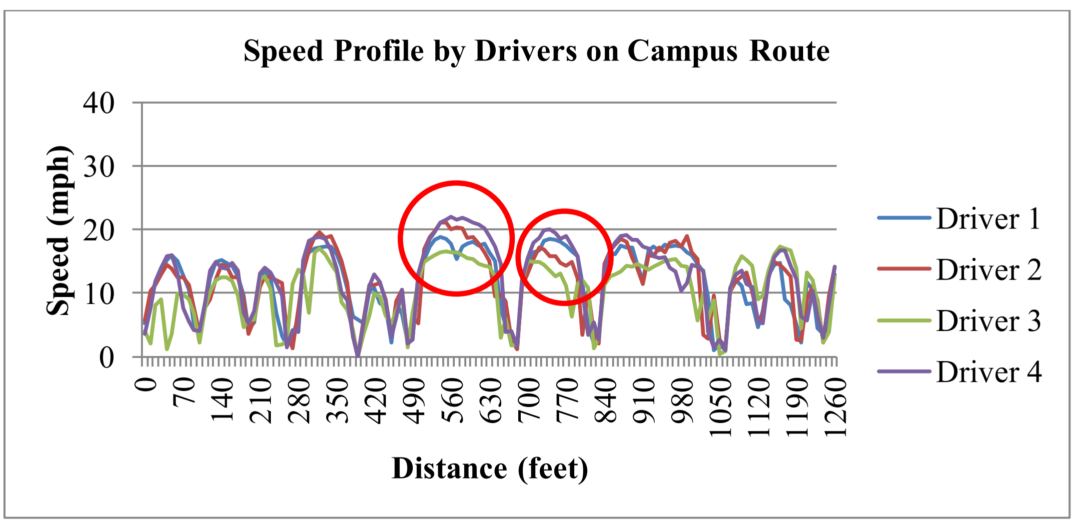


Figure 4.4 Speed profiles by drivers on campus route

4.1.2.3 VSP Bins Comparison

Figure 4.5 and 4.6 plots the distribution of VSPs, which indicates the distribution of external loadings by bus types. The vehicle specific powers are categorized into different VSP bins. Ideally, those VSP bins should be created by using classification and regression tree (CART) method to maximize the differences between the bins. However, CLEAR (2002) recommended to create bins with 2 m^2/s^3 incremental for simplicity, which is adopted in this study. Unsurprisingly, the external loadings were very similar between hybrid buses and regular buses for the same route. Additionally, the distributions of VSP on arterial route are dispersed more widely towards the two tails, which indicates higher power demanding on arterial route. From the figure 4.5 and figure 4.6, we can also found the distributions of positive VSPs are symmetrical to negative VSPs.

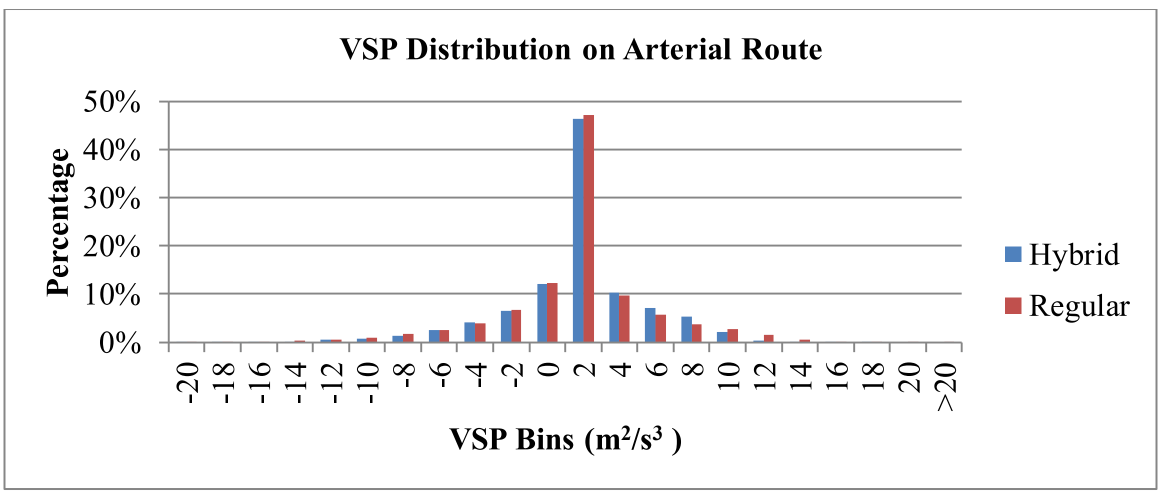


Figure 4.5 VSP comparison between hybrid buses and regular buses on arterial route

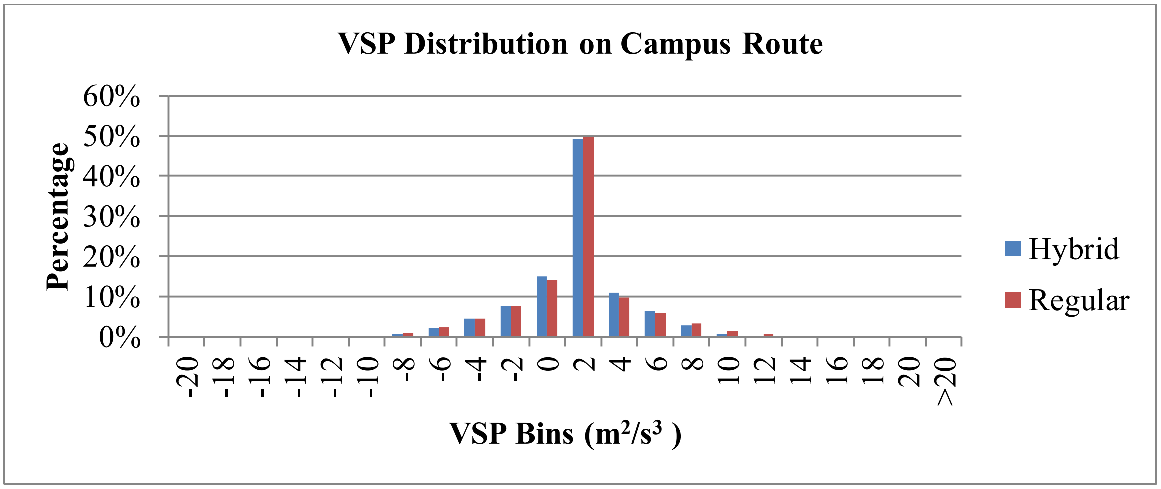


Figure 4.6 VSP comparison between hybrid buses and regular buses on campus route

In summary, this section conducted the exploratory analysis on driving behavior parameters and the major findings are shown as follows.

1) The driving activities were similar between hybrid buses and regular buses.
2) The driving behavior was different on two different routes.
3) The drivers brought a large variability in speed profiles.
4) The distribution of VSP bins showed the hybrid buses and regular buses were subjected to similar external loadings.

Based on the exploratory analysis, the route type and driver factors brought large variability in driving behavior parameters. However, no obvious differences were found between hybrid buses and regular buses. The findings were observational and those observational findings should be confirmed by statistical analysis at next section.

4.2 Nonparametric ANOVA for driving behavior analysis

Section 4.2 tests the impact of drivers and bus types on driving behavior parameters using nonparametric analysis of variance. The parametric analysis of variance (ANOVA) method was proposed at first, but the normality assumptions are grossly violated. Instead, the nonparametric method is used to conduct statistical test.

4.2.1 Flow chart for Statistical Analysis

The following flow chart illustrates the process of statistical analysis in section 4.2. In general, the procedures were used to choose statistical test between parametric two-way ANOVA or nonparametric test.

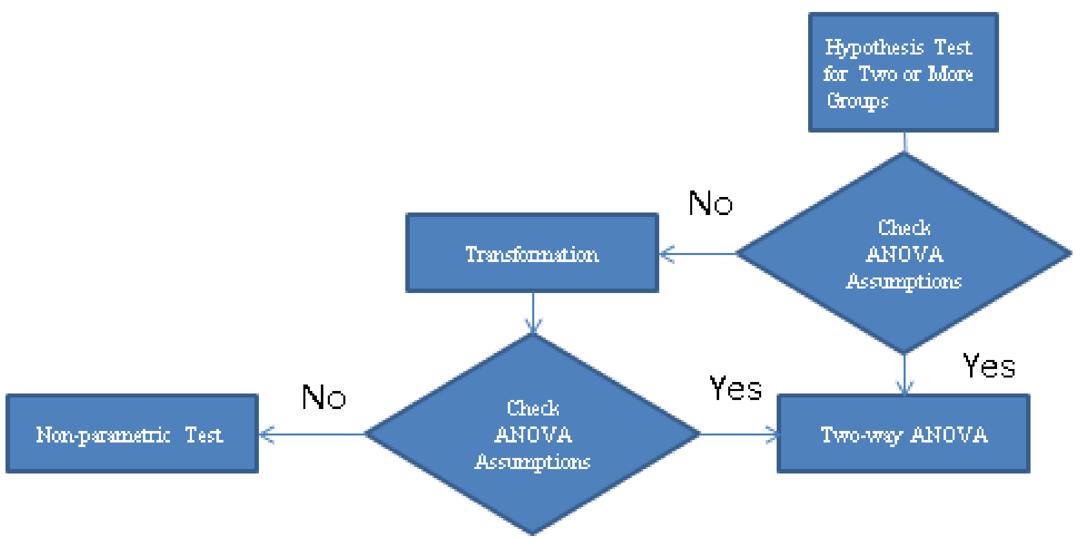


Figure 4.7 Flow char for nonparametric ANOVA analysis

4.2.2 ANOVA Assumptions

The parametric ANOVA was proposed first to test research hypothesis. In order to use ANOVA properly, the dataset has to satisfy three assumptions, which are homogeneous variance, normality, and independence. ANOVA can handle all but the most extreme violations. The serious violation of ANOVA assumptions can affect the p-value for the F-test.

4.2.2.1 Check independence assumption

The independence assumption means that observations are drawn independently from each other. Independence is usually achieved by random within experimental design. However, this study was observational and the driver factor could not be controlled in this study. This study assumed that the observations at each intersection were drawn independently from each other.

4.2.2.2 Check constant variance assumption

Constant variance assumption means the variance within each treatment group should be homogeneous. However, the equal sample sizes for each treatment group could warranty the constant variance assumption. The sample sizes were 20 for all treatment groups in this study so that the data was robust against unequal variance. In order to double check the variance assumption, the Levene test was conducted and the test hypothesis test is shown below.

H_o: $\sigma_1^2 = \sigma_2^2 = \cdots = \sigma_n^2$ (Group variances are equal)

H_a: At Least two group variance differs from each other.

The variables with p-value larger than 0.05 indicates equal variance. It does not find any serious violation of constant variance problem.

Table 4.4 Equal variance test results (Levene Test)

Variables	Arterial Route	Campus Route
	Levene Test	Levene Test
Moving Speed	0.2644	0.0038**
Acceleration	0.8585	0.0477*
Max Acceleration	0.0382	0.0047**
Std. Acceleration	0.006	0.0010***
Deceleration	0.2933	0.701
Max Deceleration	0.1463	0.2738
Std. Deceleration	0.5145	0.0124*
PKE	0.0236*	0.0451*
NKE	0.0253*	0.2352
0 < Acceleration <1	0.7699	0.8749
1 < Acceleration <2	0.8399	0.1766
3 < Acceleration	0.8218	0.1249
-1 < deceleration <0	0.1006	0.973
-2 < deceleration <-1	0.2611	0.2869
deceleration <-2	0.3937	0.0457*

Significance levels: *** = p<0.001, ** = p <0.01, * = p<0.05

4.2.2.3 Check normality assumption

In order to use F-test in ANOVA table, the observations in each group should come from normal distribution. The normality was checked by using the Shapiro-Wilk W test in JMP 9.0. The null hypothesis (H_o) is that the data is from normal distribution. The alternative hypothesis test (H_a) is that the data is not from normal distribution. The normality test results are shown in table 4.5.

Table 4.5 Normality test results

Variables	**Arterial Route**	**Campus Route**
	Shapiro-Wilk W Test	**Shapiro-Wilk W Test**
Moving Speed	0.0013***	0.0972
Acceleration	0.0260*	0.0009***
Max Acceleration	<0.0001***	<0.0001***
Std. Acceleration	<0.001***	<0.0001***
Deceleration	0.0003**	<0.0001***
Max Deceleration	<0.0001***	<0.0001***
Std. Deceleration	<0.0001***	<0.0001***
PKE	<0.0001***	<0.0001***
NKE	<0.0001***	<0.0001***
0 < Acceleration <1	<0.0001***	<0.0001***
1 < Acceleration <2	<0.0001***	<0.0001***
3 < Acceleration	<0.0001***	<0.0001***
-1 < deceleration <0	<0.0001***	<0.0001***
-2 < deceleration <-1	<0.0001***	<0.0001***
deceleration <-2	<0.0001***	<0.0001***

Significance levels: *** = p<0.0001, ** = p <0.01, * = p<0.05

The variables that were labeled with asterisks were rejected for normal distribution. As you can see in table 4.5, most of those variables did not come from normal population. Several transformation techniques were tried to convert the data into normal distribution.

3.2.2.4 Transformation Techniques

Several transformation techniques were used to transform the driving behavior parameters into normal distribution. The Box-Cox transformation was used to fit the model, but the residuals plots did not follow normal distribution. Other transformation techniques, such as log-transformation and exponential transformation, were used to transform the data. The transformed data still did not follow normal distribution. Therefore, the nonparametric method was proposed to analyze the data.

4.2.3 Nonparametric ANOVA Methodology

Since the normality assumption of parametric ANOVA was grossly violated, non-parametric was used in this study. The non-parametric method makes no assumption about the underlying population parameters. The use of ranked data requires stronger evidence to reject null hypothesis, which reduces the statistical power. Therefore, a tradeoff has to be made about whether to use parametric or nonparametric test. The nonparametric technique is only recommended when assumptions of parametric test are violated significantly.

The Kruskal-Wallis test is the nonparametric analysis test that equivalent to single factor analysis of variance. It is applicable when the data are ranked, samples are independent, and the populations are not normally distributed. All observations were all first ranked from smallest to largest denoted from 1 to n. R1 is defined as the sum of the ranks for sample1;, R2 is defined as the sum of ranks for sample 2; Rk is the sum of he ranks from sample k. The Kruskal-Wallis test statistics is defined as follows.

$$W = \frac{12}{n(n+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(n+1)$$

The test statistics D is defined as the difference between the average ranks of the sample (D=|Ri-Rj|). The Kruskal-Wallis test compares test statistics D with the critical valueC_{kw}. The null hypothesis is rejected if and only if D>C_{kw}.

4.2.4 Nonparametric Test Hypothesis

This section focused on the impacts of bus types and drivers on driving behavior. The following hypotheses were constructed to be tested by nonparametric analysis of variance.

α_i= The effect due to ith level of bus type;

β_j = The effect due to jth level of bus driver;

1) Does bus type affect driving behavior?

   H_o: Bus type does not affect driving behavior. $\alpha_1 = \alpha_2$

   H_a: Bus type affects driving behaviors. $\alpha_1 \neq \alpha_2$

2) Does driver affect driving behavior?

   H_o: Driver does not affect driving behavior. $\beta_1 = \cdots = \beta_6$

   H_a: Driver affects driving behavior. At least two β_i are not equal.

3.2.4 Nonparametric Test Results

The nonparametric tests were conducted by using JMP 9.0. The nonparametric ANOVA results are shown in table 4.6 for arterial route and table 4.7 for campus route.

Table 4.6 Results of nonparametric statistical test on arterial route

Parameter (Arterial)	Measure Type	Significant Differences	
		Bus Types	Drivers
Average Speed	Level	0.4419	0.0184*
Acceleration	Level	0.0005*	0.1052
Max Acceleration	Level	0.3359	0.0200*
Standard Deviation Acceleration	Level	0.6281	0.0075*
Deceleration	Level	0.1416	<0.0001*
Max Deceleration	Level	0.0355*	<0.0001*
Standard Deviation Deceleration	Level	0.1431	<0.0001*
PKE	Energy	0.3113	0.0020*
NKE	Energy	0.0377*	0.0006*
ACC1	Distribution	0.0518	0.0185*
ACC2	Distribution	0.3523	<0.0001*
ACC3	Distribution	0.0659	0.1197
DEC1	Distribution	0.7788	0.0689
DEC2	Distribution	0.5012	<0.0001*
DEC3	Distribution	0.2209	<0.0001*

Significance levels: *** = p<0.001, ** = p <0.01, * = p<0.05

All independent variables were dummy variables in this analysis. The variables with three asterisks indicate stronger statistical significance, while one asterisk shows less statistical significance. In general, drivers dominated most driving behavior parameters during nonparametric analysis. The bus type only affects three driving parameters, which are acceleration, maximum deceleration, and negative kinetic energy. Based on the model results, the major findings for arterial route were shown as follows.

1) Average speeds were affected by drivers with statistical significance.
2) Acceleration is affected by bus types with statistical significance. The contrast test shows the hybrid buses accelerated slower than regular buses.
3) The maximum acceleration and standard deviation of acceleration were affected by drivers.
4) Deceleration was affected by drivers with statistical significance.
5) The maximum deceleration was affected by both bus types and drivers with statistical significance.
6) The standard deviation of deceleration was affected by drivers with statistical significance.
7) Positive kinetic energy was affected by drivers with statistical significance.
8) Negative kinetic energy was affected by both bus types and drivers with statistical significance.
9) The time distributions for acceleration intervals were mainly affected by drivers with statistical significance.
10) The time distribution for deceleration intervals were mainly affected by drivers with statistical significance.

Table 4.7 Results of nonparametric statistical test on campus route

Parameter (Campus)	Measure Type	Significant Differences	
		Bus Types	Drivers
Average Moving Speed	Level	0.3923	0.3091
Acceleration	Level	0.1183	0.0026*
Max Acceleration	Level	0.0406*	0.0003*
Standard Deviation Acceleration	Level	0.0012*	0.0019*
Deceleration	Level	0.0160*	0.0030*
Max Deceleration	Level	0.5382	0.0103*
Standard Deviation Deceleration	Level	0.481	0.0027*
PKE	Energy	<0.0001*	0.0087*
NKE	Energy	<0.0001*	0.0196*
ACC1	Distribution	0.8707	0.4752
ACC2	Distribution	0.2953	0.0808
ACC3	Distribution	0.6803	0.1565
DEC1	Distribution	0.0010*	0.1245
DEC2	Distribution	0.8832	0.1277
DEC3	Distribution	0.6919	0.0174*

Significance levels: *** = p<0.001, ** = p <0.01, * = p<0.05

Table 4.7 showed the nonparametric test result for campus route. As shown in campus route, all dependent variables were dummy variables in this study. The variables with three asterisks indicate strongest statistical significance, while one asterisk shows less statistical significance. Based on the model results, the major findings for campus route were shown as follows.

1) The average speeds were not affected by either bus types or drivers with statistical significance.
2) The acceleration on campus route was affected by drivers, instead of bus types.
3) Maximum acceleration was affected by both bus types and drivers with statistical significance.
4) Standard deviation of acceleration was affected by both bus types and drivers with statistical significance.
5) Deceleration was affected by both bus types and drivers with statistical difference.
6) Maximum deceleration and standard deviation of deceleration was affected by drivers with statistical significance.
7) Positive kinetic energy and negative kinetic energy were affected by both bus types and drivers with statistical significance.
8) The distribution of acceleration was not affected by either bus types or drivers with statistical significance.
9) The time distribution for deceleration less than 1mph/s is affected by bus types with statistical significance.
10) The time distribution for deceleration larger than 3mph/s is affected by drivers with statistical significance.

Overall, the driving behavior on campus route was different than the driving behavior on arterial route, but drivers dominated most of driving behavior parameters in either case.

4.3 Regression model for driving behavior analysis

Regression model is one of the most widely used modeling methods. It can fit numerous relationships between variables with fewer constraints and the model results are also relatively easy to be interpreted. There are two different methods to calculate regression model, which are least squares estimation and maximum likelihood estimation. Both methods are thoroughly explained in most introductory statistical reference books, so it would not be explained here.

4.3.1 Regression Model Assumptions

It is important to check the assumptions for regression model before the regression model was built. Those assumptions are examined using residual plots, which could be used to identify the most extreme violation of regression assumptions. The residual plot tests the linearity, homoscedastic disturbances, serial correlation, and exogenous independent variables. Since moderate deviations of assumptions have negligible influence, the residual plot is appropriate to test the assumptions for regression model. The six main assumptions for regression models are shown in table 4.8. Based on the graphical plots, the assumptions were not violated seriously. The regression model could be used in this study.

Table 4.8 Assumptions for regression model

Statistical Assumption	Mathematical Expression
1. Functional form	$Y_i = \beta_0 + \beta_1 X_{1i} + \varepsilon_i$
2. Zero mean of disturbances	$E[\varepsilon_i] = 0$
3. Homoscedasticity of disturbances	$VAR[\varepsilon_i] = \sigma^2$
4. Non-autocorrelation of disturbances	$COV[\varepsilon_i, \varepsilon_j] = 0$, if $i \neq j$
5. Uncorrelatedness of regressor and disturbances	$COV[Xi, \varepsilon_j] = 0$, for all i and j
6. Normality of disturbance	$\varepsilon_i \approx N(0, \sigma^2)$

Source: Statistical and econometric methods for transportation data analysis.

4.3.2 Multivariate Correlations

Before building the regression model, decisions needs to be made about which variables to be included in the model. The most common way to do this is to check the pairwise correlations among all variables. All those variables with high correlation coefficients were tried to fit the regression models. The correlations were checked by using Multivariate command in JMP 9.0.

4.3.3 Regression Model Results and Discussion

Regression models are built for each driving parameter on arterial route and campus route. Since there are thirty regression models in total, those regression model outputs are shown in appendix. Since the regression models are very similar, this section only explains the regression model for acceleration parameter on arterial route as an example. Other regression models could be explained in similar way.

Table 4.9 Regression model outputs for acceleration on arterial route

Parameter	**Parameter Estimate**	**Standard Error of Estimate**	**t-Value**	**P(>|t|)**
Intercept	1.463	0.12	12.17	<0.001*
Regular bus	0.048	0.016	3.07	0.0024*
Max ACC	0.056	0.008	6.93	<0.001*
Average Deceleration	-0.192	0.042	-4.58	<0.001*
Speed	-0.019	0.007	-2.62	0.0094
R-Square	0.248			
R-square Adjust	0.235			
RMSE	0.239			
Observations	240			
Model F-Statistic	<0.0001*			

The model outputs are explained as follows:

1) The null hypothesis for the regression model is $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$, which indicates all coefficients in the model are zero. Since the p value for F-statistics is less than 0.0001, the null hypothesis is rejected and at least one coefficient is not zero.
2) The R-square is 0.248, which indicates the portion of variation explained by the mode. The R-square equals to one indicates perfect fit. The R-square adjust is 0.235 is an alternative to R-square based on the formula Adjusted $R^2 = 1 - (1 - R^2)\frac{n-1}{n-m-1}$, where n is the number of observations and m is the number of parameters. The R-

square adjust is used to account the effect of improving model fit by simply adding many superfluous variables to the model.

3) The equation of the fitted model is *acceleration = 1.463 +(0.048)(bustype)+(0.056)*(maxacc)-(0.192)*(deceleration)-(0.019)(speed).* The speed variable could be used as an example to explain the coefficients. One unit increases in speed (mph) would decrease the acceleration by 0.019 (mph/s), while holding all other factors constant.

4) The t statistics are used to test the individual parameters in regression model. The p-value less than 0.05 indicates a statistical significant effect due to the parameter.

4.4 Models Results Comparison between Nonparametric ANOVA and Regression Model

Since the dataset does not satisfy the normality assumption for ANOVA, non-parametric analysis was conducted to check the impact of drivers and bus types on driving behavior in section 4.2. The regression models were also built in section 4.3 to include some other variables in the model, such as intersections, peak hour, and ridership. Only those variables that statistically significant were kept in the regression model. Since two techniques were used to fit the same dataset, this section compares the statistical test results between the two modeling methods.

Table 4.10 Model comparison on arterial route

Parameter (Arterial)	Measure Type	Non-parametric Significant Difference		Regression Model Significant Difference	
		Bus Types	Drivers	Bus Types	Drivers
Average Moving Speed	Level		0.0184*		0.0012*
Acceleration	Level	0.0005*		0.0024*	
Max Acceleration	Level		0.0200*		0.0017*
Standard Deviation Acceleration	Level		0.0075*		00002*
Deceleration	Level		<0.0001*	0.008*	<0.0001*
Max Deceleration	Level	0.0355*	<0.0001*		0.0001*
Standard Deviation Deceleration	Level		<0.0001*		<0.0001*
PKE	Energy		0.0020*		0.0121*
NKE	Energy	0.0377*	0.0006*		<0.0001*
ACC1	Distribution		0.0185*		0.0023*
ACC2	Distribution		<0.0001*		0.0173*
ACC3	Distribution				0.0022*
DEC1	Distribution				0.0002*
DEC2	Distribution		<0.0001*		<0.0001*
DEC3	Distribution		<0.0001*		0.0235*

Note: The cells with yellow color indicate that the two models have different hypothesis test results.

Table 4.11 Model comparison on campus route

		Non-parametric		Regression Model	
Parameter (Arterial)	Measure Type	Significant Difference		Significant Difference	
		Bus Type	Driver	Bus Type	Driver
Average Moving Speed	Level				
Acceleration	Level		0.0026*	0.0115*	0.0041*
Max Acceleration	Level	0.0406*	0.0003*		0.0104*
Standard Deviation Acceleration	Level	0.0012*	0.0019*	0.0405*	0.0004*
Deceleration	Level	0.0160*	0.0030*		0.0005*
Max Deceleration	Level		0.0103*	0.0368*	
Standard Deviation Deceleration	Level		0.0027*		0.0045*
PKE	Energy	<0.0001*	0.0087*	0.0003*	0.0142*
NKE	Energy	<0.0001*	0.0196*		0.0164*
ACC1	Distribution				
ACC2	Distribution			0.0401*	0.0007
ACC3	Distribution				0.0093*
DEC1	Distribution	0.0010*		0.0078*	
DEC2	Distribution				0.0002*
DEC3	Distribution		0.0174*		0.0263*

Note: The cells with yellow color indicate that the two models have different hypothesis test results.

Table 4.10 and table 4.11 compared the statistical testing results for both bus type and driver variables. The yellow color labels the statistical results that different between the two models. In general, the testing results are similar between the two methods. It is not surprising to see some statistical testing results are different between the two methods because they were using two different techniques to estimate the test statistics. The nonparametric conducted statistical tests based on rankings while the regression model is based on actual values by using F-statistics. If findings are disagree between two models, it is recommended to use the findings from nonparametric method since it is more easily to reject any hypothesis if evidences are not strong. This could reduce the chance to reject on the null hypothesis falsely.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the major findings, contributions to state-of-the-art, limitations, and recommendations for future research.

5.1 Summary of Major Findings

Several driving behavior studies found the route type, bus type, and driver factors contributed to the variability of driving behavior parameters, but none of those studies were conducted on hybrid bus. This study used GPS data loggers to measure bus activities. Both nonparametric ANOVA and regression model was used to test which factors affect driving behavior with statistical significance, the major findings from the driving behavior analysis is listed below.

Arterial Route

1) The acceleration was mainly affected by bus types. The comparison test showed the hybrid buses accelerated slower than regular buses. It may be caused by the extra weights of battery pack on hybrid bus, but it needs further investigation.
2) Driver is the main factor that affects the deceleration.
3) The aggressive acceleration and aggressive deceleration are usually dominated by drivers.
4) The kinetic energy was usually affected by drivers.
5) The distribution of time in acceleration intervals were mainly affected by drivers.

Campus Route

1) The average speeds on campus route were not affected by either bus types or drivers.
2) The acceleration on campus route was affected by drivers, instead of bus types.
3) The deceleration on campus route was mainly affected by drivers.
4) The kinetic energy parameters were mostly affected by both bus types and drivers.
5) The distribution of time in different acceleration intervals were affected by both bus types and drivers.

Model Comparison

Two types of models were built in this study. One was nonparametric ANOVA and another one was regression model. Most of statistical testing results were similar between the two models, but some parameters did not agree with each other between the two models. Since the nonparametric are more conservative to reject null hypothesis, it is prefer to draw conclusion based on nonparametric model to avoid rejecting null hypothesis falsely.

5.2 Contributions to State-of-the-Art

This research addressed fuel economy and driving behavior of hybrid bus and contributions to state-of-the-art are summarized below.

1) This was the first study to test the on-road driving behavior for hybrid bus.
2) This study found that the driving behavior were different by route types.
3) This study found that hybrid bus accelerated slower than regular diesel bus on average due to extra weights.

4) Although hybrid bus had regenerative braking system, no previous study compared the deceleration between hybrid bus and regular bus. This study found that hybrid bus and regular bus decelerated similarly. The dominant factor that affected deceleration of hybrid bus was drivers.

5.3 Assumptions

Some important assumptions were made during this study. Those assumptions were summarized below:

1) The driver was assumed not to change their driving behavior by knowing the on-going data collection on the buses. Otherwise, they might be felt being monitored and change their driving behavior accordingly.
2) The observations were assumed to be drawn independently and randomly at different intersections.
3) The traffic condition was not included in the driving behavior analysis.

5.4 Limitations

There were some limitations in this research.

1) The drivers might go through a learning curve about how to drive hybrid bus, but this effect was not included in the analysis.
2) Since the bus drivers' schedule was fixed, we could not control the driver factor during data collection. It resulted in less efficient experiment design.

3) All CyRide bus routes were operated on roads with equal or less than 30 mph speed limits. There was no high speed driving in this study. Therefore, we did not know how hybrid buses performed at high speed.
4) We did not record any on-board diagnostic information, such as engine speed, power split between electric motor and diesel engine, state of the battery charge, braking pedal position, etc. The information could be useful to characterize how hybrid bus performed differently than regular diesel bus.

5.5 Recommendations for Future Research

Several recommendations are proposed to better understand the hybrid bus performances in the future.

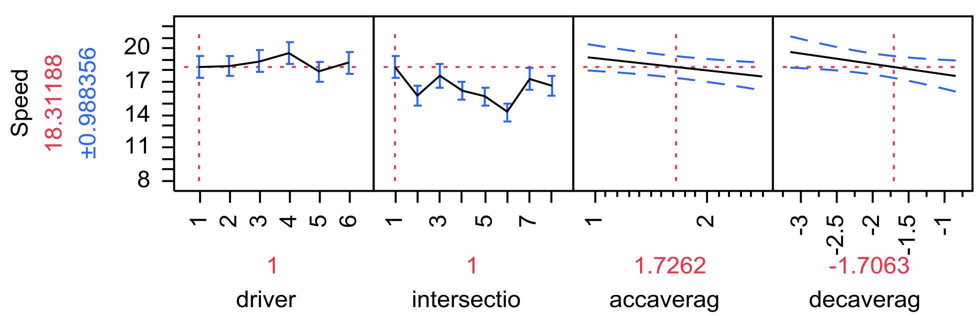
1) It is recommended to control driver variable, bus type, route, and peak hour factors in experimental design. A well-conducted experiment design could lead to good data analysis with least cost.
2) In order to better understand how hybrid bus performs differently from regular bus, it is recommended to record some parameters from the on-board diagnostic, such as regenerative braking pedal position, state of charge of battery, and the performance of electric motor. This information is important to characterize some important features of hybrid bus.
3) It is also recommended to evaluate emissions of hybrid bus in future study.

APPENDIX REGRESSION MODEL OUTPUTS

Speed Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	17.062	1.002	17.02	<0.0001*
Intersection1	1.871	0.361	5.18	<0.0001*
Intersection2	-0.714	0.312	-2.29	0.0232*
Intersection3	1.086	0.376	2.89	0.0043*
Intersection5	-0.769	0.327	-2.35	0.0197*
Intersection6	-2.165	0.315	-6.88	<0.0001*
Intersection7	0.788	0.384	2.05	0.0414*
Driver1	17.062	1.002	-1.11	<0.001*
Driver5	-0.698	0.29	-2.34	0.0012*
ACC	-1.114	0.47	-2.37	0.0185*
DEC	-0.943	0.46	-2.05	0.0414*
R-Square	0.416			
Rsquare Adj	0.379			
RMSE	1.88			
Observations	240			
Model F-Statistic	<0.001*			

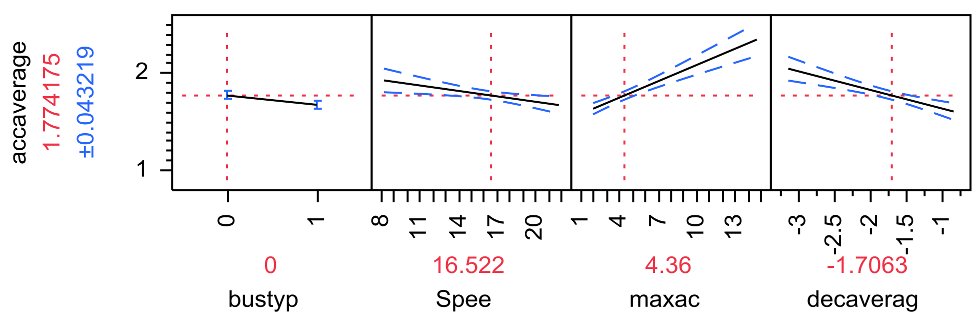
Factor Profiler



Acceleration Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	1.463	0.12	12.17	<0.001*
Bus Type	0.048	0.016	3.07	0.0024
Max ACC	0.056	0.008	6.93	<0.001*
Average Deceleration	-0.192	0.042	-4.58	<0.001*
Speed	-0.019	0.007	-2.62	0.0094
R-Square	0.248			
Rsquare Adj	0.235			
RMSE	0.239			
Observations	240			
Model F-Statistic	<0.0001*			

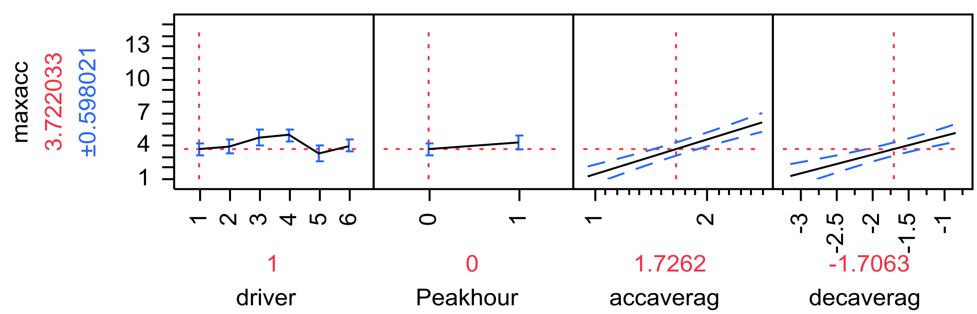
Factor Profiler



Maximum Acceleration Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	1.885911445	0.815144553	2.31	0.0216
Driver2	-0.180794707	0.249289764	-0.73	0.469
Driver3	0.631387663	0.279801395	2.26	0.025
Driver4	0.89600914	0.282924744	3.17	0.0017
Driver5	-0.799244013	0.286411839	-2.79	0.0057
Peakhour	-0.298609463	0.146591548	-2.04	0.0428
ACC	3.145797613	0.419144079	7.51	<.0001
DEC	1.69637587	0.317523222	5.34	<.0001
R-Square	0.252			
Rsquare Adj	0.226			
RMSE	1.707			
Observations	240			
Model F-Statistic	<0.0001*			

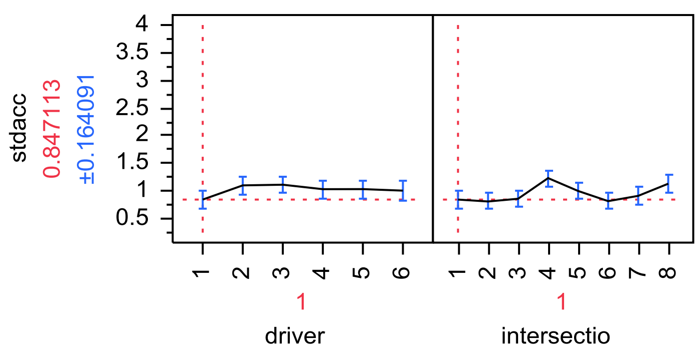
Factor Profiler



Standard Deviation of Acceleration Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	1.130584205	0.021396932	52.84	<.0001
Driver1	-0.177249008	0.047087231	-3.76	0.0002
Intersection2	-0.1404937	0.052788742	-2.66	0.0083
Intersection4	0.281840981	0.051396222	5.48	<.0001
Intersection5	0.049156192	0.056000992	0.88	0.381
R-Square	0.231			
Rsquare Adj	0.19			
RMSE	0.323			
Observations	240			
Model F-Statistic	<0.0001*			

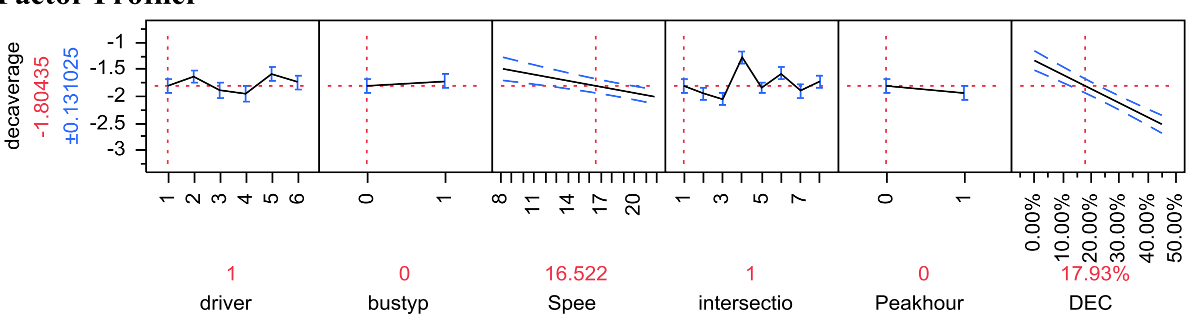
Factor Profiler



Deceleration Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	-0.650667918	0.159318499	-4.08	<.0001
Driver2	0.131963519	0.033539894	3.93	0.0001
Driver3	-0.120152974	0.03867378	-3.11	0.0021
Driver4	-0.186025423	0.038070431	-4.89	<.0001
Driver5	0.180058308	0.038733189	4.65	<.0001
Bus Type	-0.040786258	0.015249791	-2.67	0.008
Speed	-0.037926979	0.008285236	-4.58	<.0001
Intersection2	-0.178822825	0.037987038	-4.71	<.0001
Intersection3	-0.28988911	0.043451372	-6.67	<.0001
Intersection4	0.489200126	0.040842168	11.98	<.0001
Intersection6	0.180747814	0.040502694	4.46	<.0001
Intersection7	-0.127732797	0.046841742	-2.73	0.0069
peakhour	0.066706019	0.020183022	3.31	0.0011
DEC3	-2.630179438	0.266487722	-9.87	<.0001
R-Square	0.709			
Rsquare Adj	0.689			
RMSE	0.229			
Observations	240			
Model F-Statistic	<0.0001*			

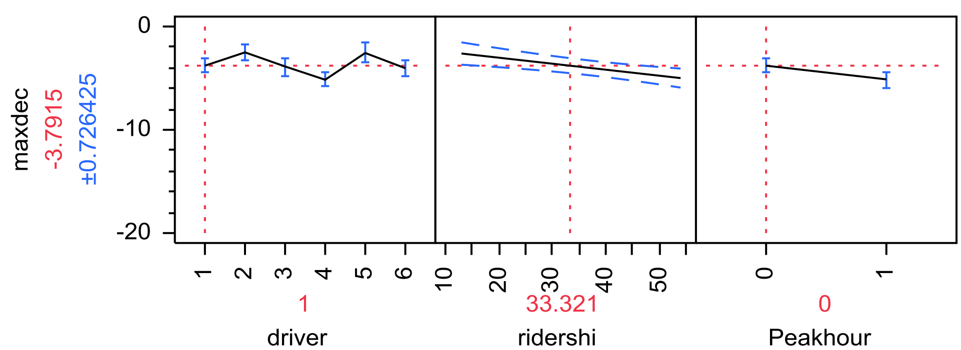
Factor Profiler



Maximum Deceleration Regression Model on Arterial Route

Parameter	**Parameter Estimate**	**Standard Error of Estimate**	**t-Value**	**P(>|t|)**
Intercept	-2.379328736	0.571624637	-4.16	<.0001
Driver2	1.148570321	0.332998996	3.45	0.0007
Driver4	-1.500868679	0.379617222	-3.95	0.0001
Driver5	1.090941753	0.357591627	3.05	0.0025
Ridership	-0.058031483	0.017204993	-3.37	0.0009
Peakhour	0.661560004	0.19517806	3.39	0.0008
R-Square	0.123			
Rsquare Adj	0.096			
RMSE	2.047			
Observations	240			
Model F-Statistic	<0.0001*			

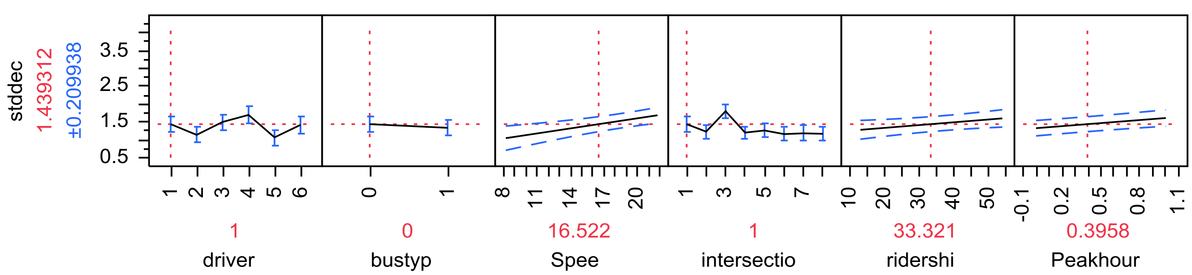
Factor Profiler



Standard Deviation of Deceleration Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.042120227	0.263626524	0.16	0.8732
drivers2	-0.23848102	0.064483422	-3.7	0.0003
drivers3	0.123543202	0.062924276	1.96	0.0508
drivers4	0.320474501	0.073808877	4.34	<.0001
drivers5	-0.308614366	0.068890616	-4.48	<.0001
regular	0.051293125	0.027781824	1.85	0.0662
Speed	0.047043112	0.013381913	3.52	0.0005
intersection3	0.496311547	0.073000857	6.8	<.0001
intersection6	-0.145208046	0.065729839	-2.21	0.0282
ridership	0.007817891	0.003537943	2.21	0.0281
Peakhours	0.284881493	0.074034364	3.85	0.0002
R-Square	0.4457			
Rsquare Adj	0.4059			
RMSE	0.383			
Observations	1.177			
Model F-Statistic	<0.0001*			

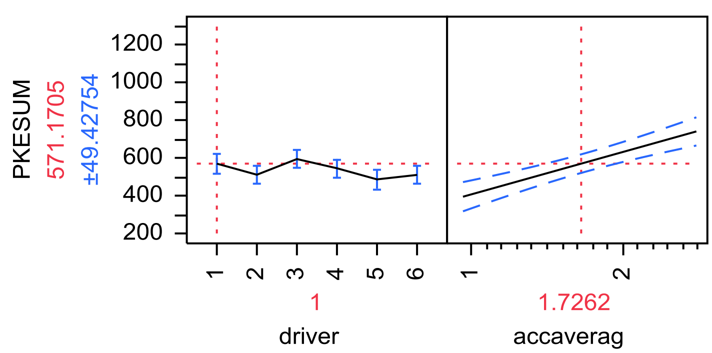
Factor Profiler



PKE Regression Model on Arterial Route

Parameter	**Parameter Estimate**	**Standard Error of Estimate**	**t-Value**	**P(>|t|)**
Intercept	151.7396823	66.37514318	2.29	0.0231
Driver3	58.18941901	22.99819498	2.53	0.0121
Driver5	-49.89055057	22.95517157	-2.17	0.0308
ACC	223.4065053	37.99034376	5.88	<.0001
R-Square	0.178			
Rsquare Adj	0.156			
RMSE	158.635			
Observations	240			
Model F-Statistic	<0.0001*			

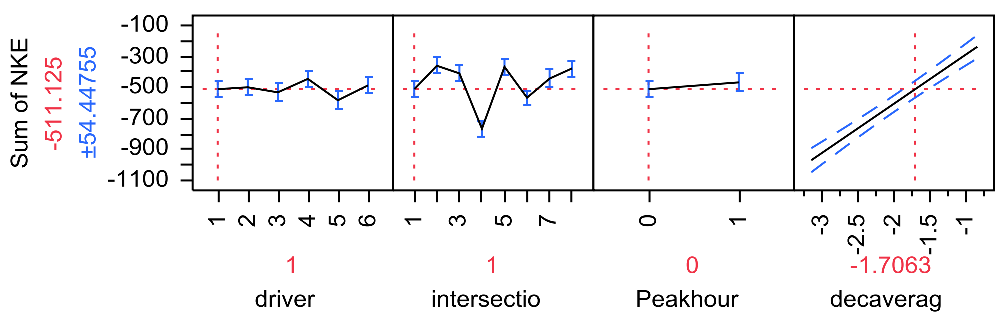
Factor Profiler



NKE Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	91.81113392	42.99558482	2.14	0.0338
Driver4	64.56833389	17.07600339	3.78	0.0002
Driver5	-73.36722442	17.57226449	-4.18	<.0001
Intersection2	114.8196561	16.81645148	6.83	<.0001
Intersection3	65.61875761	20.3304868	3.23	0.0014
Intersection4	-291.1121818	17.95135459	-16.22	<.0001
Intersection5	107.9050063	17.59519809	6.13	<.0001
Intersection6	-91.10060821	16.94315943	-5.38	<.0001
Peakhour	-21.89402303	8.81048761	-2.48	0.0137
DEC	318.1709347	24.23098818	13.13	<.0001
R-Square	0.685			
Rsquare Adj	0.665			
RMSE	101.412			
Observations	240			
Model F-Statistic	<0.0001*			

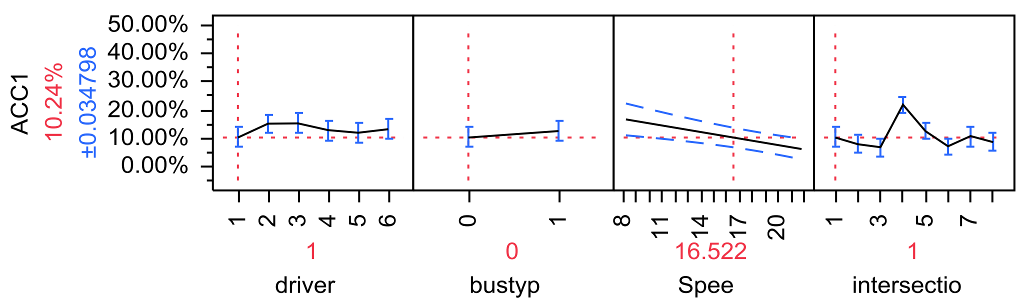
Factor Profiler



ACC1 Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.274923976	0.037681392	7.3	<.0001
drivers[1]	-0.02872412	0.009326637	-3.08	0.0023
drivers[2]	0.0204897	0.009385045	2.18	0.0301
drivers[3]	0.021499547	0.009329469	2.3	0.0221
bustype[0]	-0.011529264	0.004167475	-2.77	0.0061
Speed	-0.007712307	0.002231723	-3.46	0.0007
intersection[2]	-0.028604258	0.01052049	-2.72	0.0071
intersection[3]	-0.039217824	0.012148274	-3.23	0.0014
intersection[4]	0.111731165	0.010241961	10.91	<.0001
intersection[6]	-0.035835213	0.010936223	-3.28	0.0012
R-Square	0.449368514			
Rsquare Adj	0.415106999			
RMSE	0.063960782			
Observations	240			
Model F-Statistic	<0.0001*			

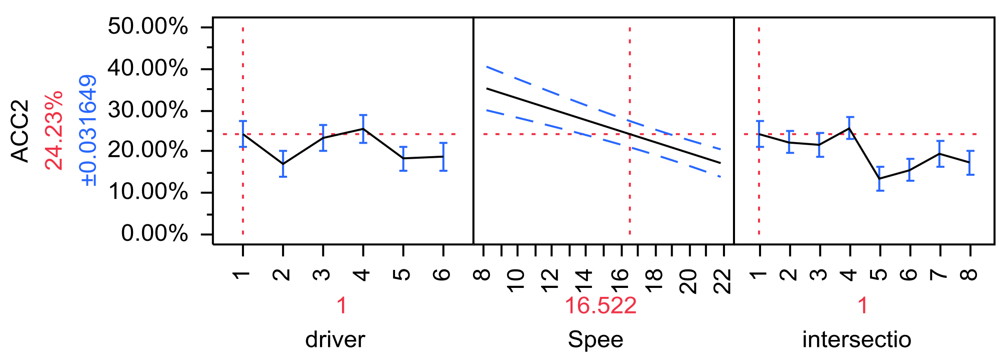
Factor Profiler



ACC2 Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.387636968	0.035358342	10.96	<.0001
drivers[1]	0.030223012	0.008763581	3.45	0.0007
drivers[2]	-0.04174635	0.008818521	-4.73	<.0001
drivers[3]	0.021023608	0.008766243	2.4	0.0173
drivers[4]	0.04284329	0.009073228	4.72	<.0001
drivers[5]	-0.028267483	0.008940278	-3.16	0.0018
Speed	-0.013219708	0.002094007	-6.31	<.0001
intersection[1]	0.04289378	0.012033175	3.56	0.0004
intersection[2]	0.022519377	0.009881925	2.28	0.0236
intersection[4]	0.0566286	0.009622004	5.89	<.0001
intersection[5]	-0.064598411	0.010513456	-6.14	<.0001
intersection[6]	-0.044500789	0.010270518	-4.33	<.0001
R-Square	0.422041622			
Rsquare Adj	0.388796228			
RMSE	0.060099918			
Observations	240			
Model F-Statistic	<0.0001*			

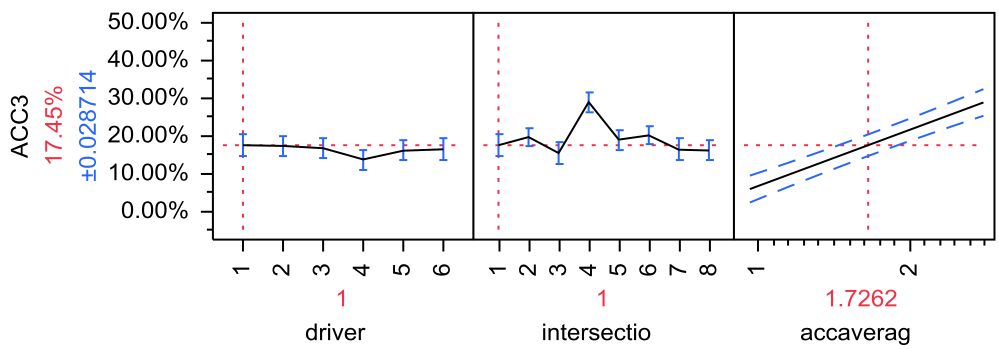
Factor Profiler



ACC3 Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	-0.077167709	0.024031821	-3.21	0.0015
Driver4	-0.025630504	0.008261315	-3.1	0.0022
Intersection2	0.005314235	0.009240227	0.58	0.5658
Intersection3	-0.037152369	0.010390125	-3.58	0.0004
Intersection4	0.098394036	0.008994757	10.94	<.0001
Intersection7	-0.028242689	0.011404035	-2.48	0.014
ACC	0.148190272	0.013722059	10.8	<.0001
R-Square	0.532			
Rsquare Adj	0.505			
RMSE	0.057			
Observations	240			
Model F-Statistic	<0.0001*			

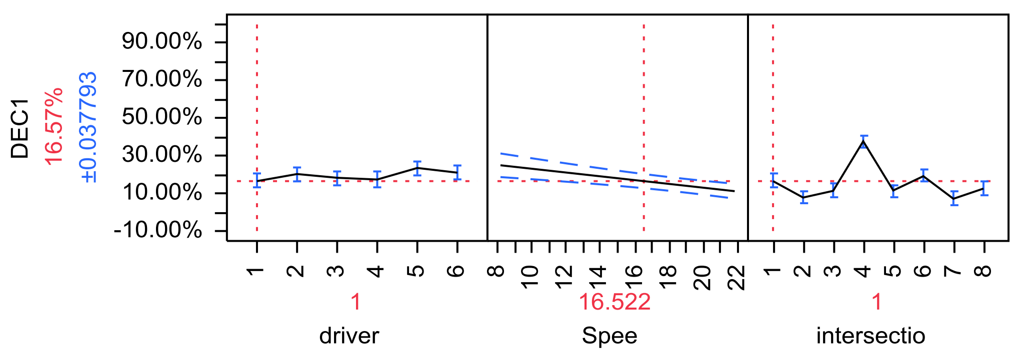
Factor Profiler



DEC1 Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.35226353	0.042222679	8.34	<.0001
drivers[1]	-0.029887528	0.01046491	-2.86	0.0047
drivers[4]	-0.021283935	0.010834671	-1.96	0.0507
drivers[5]	0.040189573	0.01067591	3.76	0.0002
Speed	-0.010115463	0.00250053	-4.05	<.0001
intersection[2]	-0.077005928	0.011800365	-6.53	<.0001
intersection[3]	-0.041309806	0.013569406	-3.04	0.0026
intersection[4]	0.222774651	0.011489984	19.39	<.0001
intersection[5]	-0.039153305	0.0125545	-3.12	0.0021
intersection[6]	0.03684471	0.012264398	3	0.003
intersection[7]	-0.083464763	0.014638294	-5.7	<.0001
R-Square	0.70402816			
Rsquare Adj	0.687003231			
RMSE	0.071767493			
Observations	240			
Model F-Statistic	0.0001*			

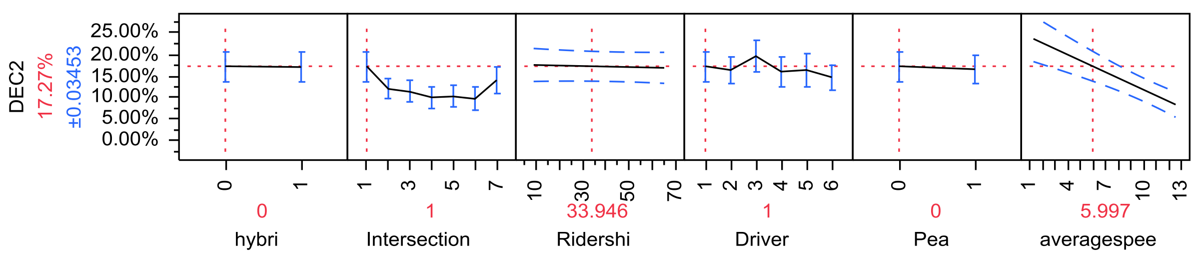
Factor Profiler



DEC2 Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.550200734	0.041288464	13.33	<.0001
drivers3	-0.031248338	0.009855028	-3.17	0.0017
drivers4	-0.030722563	0.011559744	-2.66	0.0084
drivers5	0.069196521	0.01078946	6.41	<.0001
Speed	-0.023405035	0.002095839	-11.17	<.0001
intersection2	-0.034295687	0.009902767	-3.46	0.0006
intersection3	-0.043774412	0.011433194	-3.83	0.0002
intersection4	0.098700724	0.009657585	10.22	<.0001
intersection5	-0.027485052	0.010523279	-2.61	0.0096
intersection6	0.032630763	0.010294427	3.17	0.0017
intersection7	0.02526144	0.012309019	2.05	0.0413
R-Square	0.715131641			
Rsquare Adj	0.694692655			
RMSE	0.060057878			
Observations	240			
Model F-Statistic	<0.0001*			

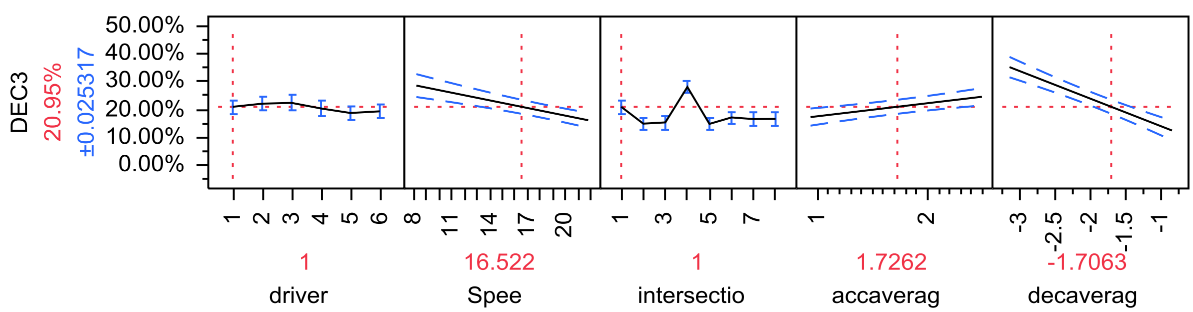
Factor Profiler



DEC3 Regression Model on Arterial Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.077629471	0.037780283	2.05	0.0411
Driver2	0.014496719	0.007039491	2.06	0.0406
Driver3	0.017333345	0.007600326	2.28	0.0235
Driver5	-0.002812739	0.007376298	-0.38	0.7033
Intersection1	0.029245416	0.009518204	3.07	0.0024
Intersection2	-0.031555043	0.007874811	-4.01	<.0001
Intersection3	-0.027107332	0.009553988	-2.84	0.005
Intersection4	0.100658859	0.008338636	12.07	<.0001
Intersection5	-0.032470342	0.008258987	-3.93	0.0001
Speed	-0.009172421	0.001661279	-5.52	<.0001
ACC	0.047184978	0.011846771	3.98	<.0001
DEC	-0.099353465	0.011564144	-8.59	<.0001
R-Square	0.607			
Rsquare Adj	0.581			
RMSE	0.047			
Observations	240			
Model F-Statistic	<0.0001*			

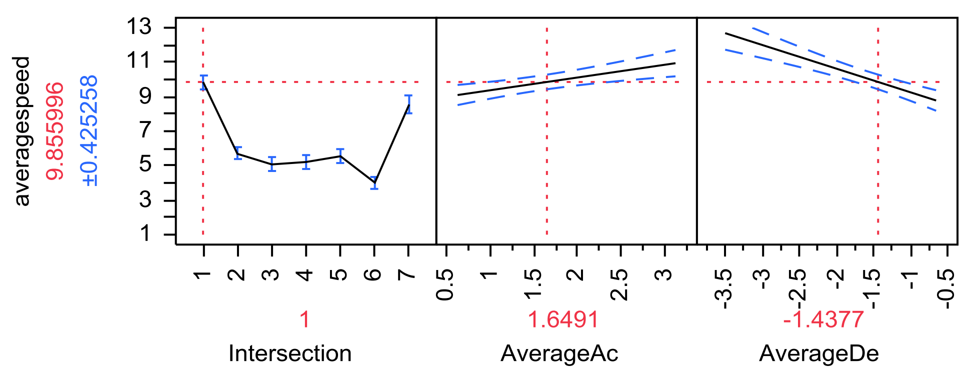
Factor Profiler



Speed Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	3.085940137	0.373495022	8.26	<.0001
Intersection1	3.578176654	0.198983738	17.98	<.0001
Intersection2	-0.591192691	0.172540347	-3.43	0.0007
Intersection3	-1.203697579	0.189469069	-6.35	<.0001
Intersection4	-1.063359454	0.188365548	-5.65	<.0001
Intersection5	-0.730464106	0.18377858	-3.97	<.0001
Intersection6	-2.259637817	0.186493692	-12.12	<.0001
ACC	0.740963329	0.210482904	3.52	0.0005
DEC	-1.370214185	0.229027838	-5.98	<.0001
R-Square	0.773			
Rsquare Adj	0.765			
RMSE	1.166			
Observations	240			
Model F-Statistic	<0.0001*			

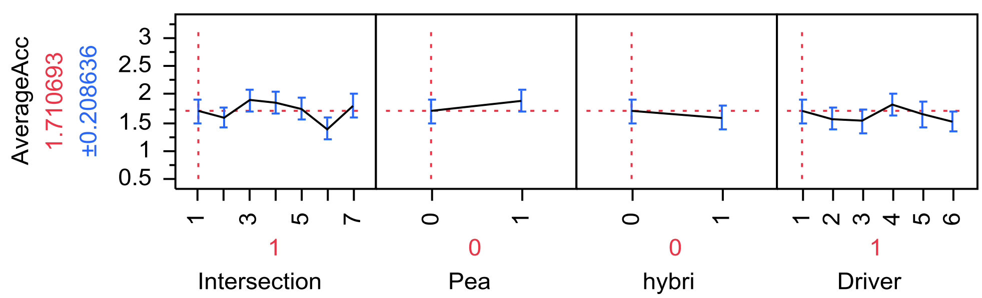
Factor Profiler



Acceleration Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	1.659691113	0.025480643	65.14	<.0001
Intersection2	-0.123680865	0.055029225	-2.25	0.0256
Intersection3	0.192941691	0.061358164	3.14	0.0019
Intersection4	0.143661505	0.060735413	2.37	0.0189
Intersection6	-0.329970865	0.056805185	-5.81	<.0001
Peak hour	-0.088431418	0.032862192	-2.69	0.0077
Bus Type	0.063833989	0.025059293	2.55	0.0115
Driver	0.188046064	0.064931086	2.9	0.0041
R-Square	0.275			
Rsquare Adj	0.233			
RMSE	0.383			
Observations	240			
Model F-Statistic	<0.0001*			

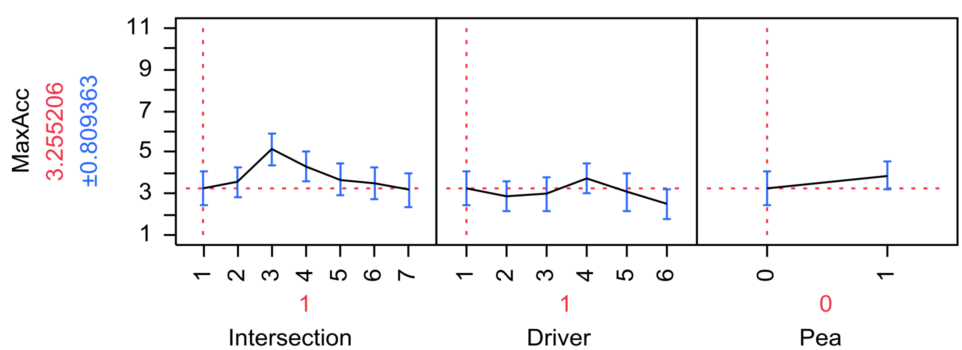
Factor Profiler



Maximum Acceleration Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	3.927859755	0.099937908	39.3	<.0001
Intersection1	-0.551158104	0.257013651	-2.14	0.0331
Intersection3	1.351895095	0.240640344	5.62	<.0001
Intersection4	0.499948843	0.238090857	2.1	0.0368
Driver4	0.656626296	0.254154625	2.58	0.0104
Peakhour	-0.298554249	0.127810997	-2.34	0.0204
R-Square	0.22			
Rsquare Adj	0.179			
RMSE	1.501			
Observations	240			
Model F-Statistic	<0.001*			

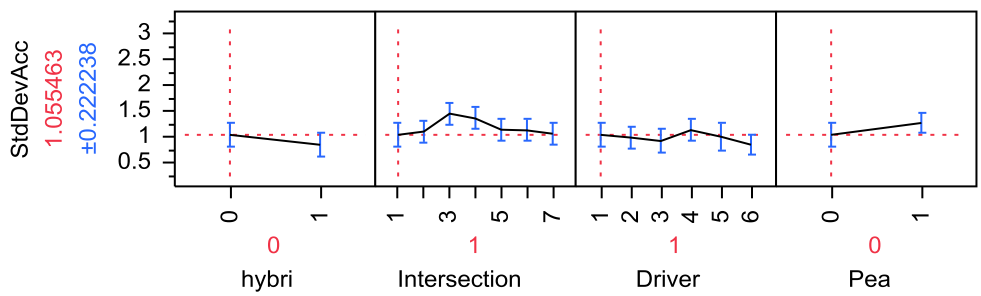
Factor Profiler



Standard Deviation Acceleration Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	1.164802328	0.027141897	42.92	<.0001
hybrid[0]	0.096209084	0.026693077	3.6	0.0004
Intersection ID[1]	-0.142405159	0.069872696	-2.04	0.0427
Intersection ID[3]	0.268232334	0.065358515	4.1	<.0001
Intersection ID[4]	0.17354814	0.064695163	2.68	0.0078
Drivers[4]	0.142481061	0.06916438	2.06	0.0405
Peak[0]	-0.114884112	0.035004699	-3.28	0.0012
R-Square	0.228477772			
Rsquare Adj	0.184098175			
RMSE	0.407732824			
Observations	240			
Model F-Statistic	<0.0001*			

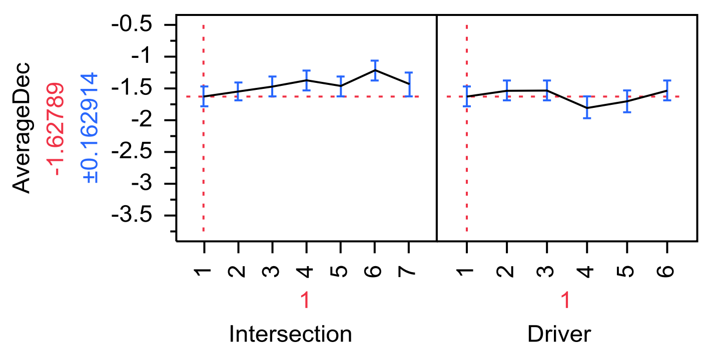
Factor Profiler



Deceleration Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	-1.442638343	0.023711756	-60.84	<.0001
Intersection1	-0.18131346	0.06070696	-2.99	0.0031
Intersection2	-0.102715634	0.051481489	-2	0.0472
Intersection6	0.233445708	0.053128705	4.39	<.0001
Driver4	-0.183793973	0.051954421	-3.54	0.0005
R-Square	0.174			
Rsquare Adj	0.134			
RMSE	0.358			
Observations	240			
Model F-Statistic	<0.0001*			

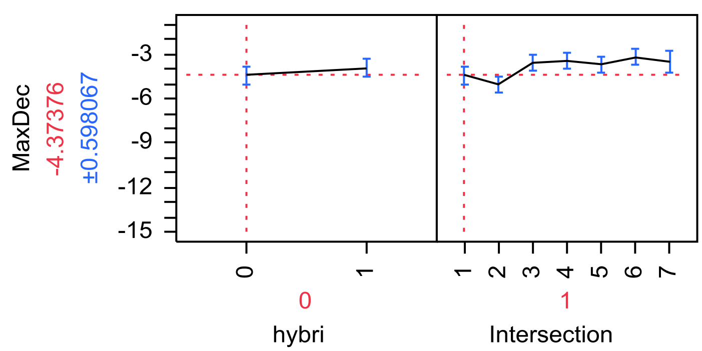
Factor Profiler



Maximum Deceleration Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	-3.607730172	0.10443658	-34.54	<.0001
Bus Type	-0.215058948	0.102426363	-2.1	0.0368
Intersection1	-0.550965898	0.265040048	-2.08	0.0387
Intersection2	-1.199022508	0.226604354	-5.29	<.0001
Intersection6	0.617750249	0.233109552	2.65	0.0086
R-Square	0.16			
Rsquare Adj	0.134			
RMSE	1.578			
Observations	240			
Model F-Statistic	<0.0001*			

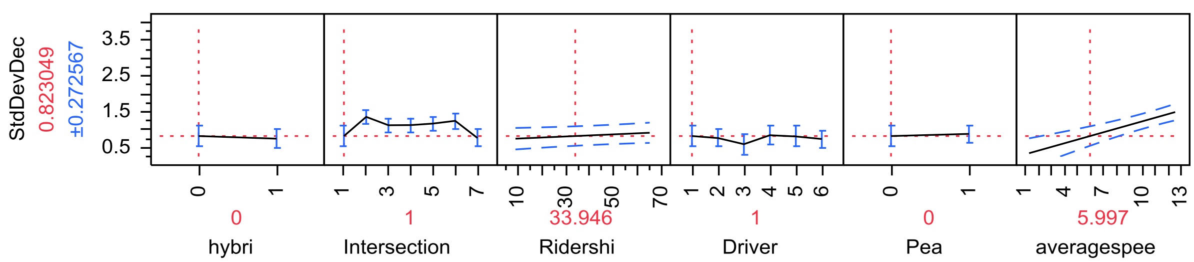
Factor Profiler



Standard Deviation of Deceleration Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.310019514	0.156522188	1.98	0.0489
Intersection ID[1]	-0.266605812	0.102522846	-2.6	0.0099
Intersection ID[2]	0.270283279	0.057066757	4.74	<.0001
Intersection ID[6]	0.159106011	0.080954922	1.97	0.0506
Drivers[3]	-0.168811454	0.058752988	-2.87	0.0045
averagespeed	0.102281924	0.020247238	5.05	<.0001
R-Square	0.236165874			
Rsquare Adj	0.185016267			
RMSE	0.389427095			
Observations	240			
Model F-Statistic	<0.0001*			

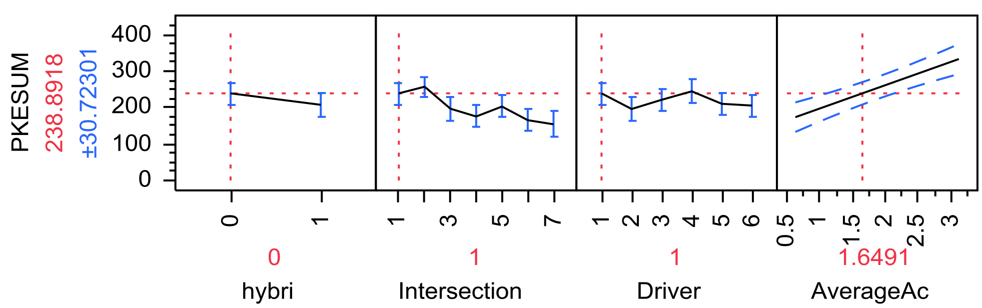
Factor Profiler



PKE Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	57.77084882	18.93926175	3.05	0.0026
Bus Type	15.72743689	4.244204069	3.71	0.0003
Intersection1	40.31025423	10.9741411	3.67	0.0003
Intersection2	58.4708458	9.401605139	6.22	<.0001
Intersection4	-23.18137967	10.39140949	-2.23	0.0267
Intersection6	-33.29781351	10.27077699	-3.24	0.0014
Driver1	19.56111876	9.470612763	2.07	0.04
Driver2	-23.38424001	9.46242671	-2.47	0.0142
Driver4	25.06447512	9.447277193	2.65	0.0085
ACC	63.98771119	11.06788597	5.78	<.0001
R-Square	0.417			
Rsquare Adj	0.384			
RMSE	64.701			
Observations	240			
Model F-Statistic	<0.0001*			

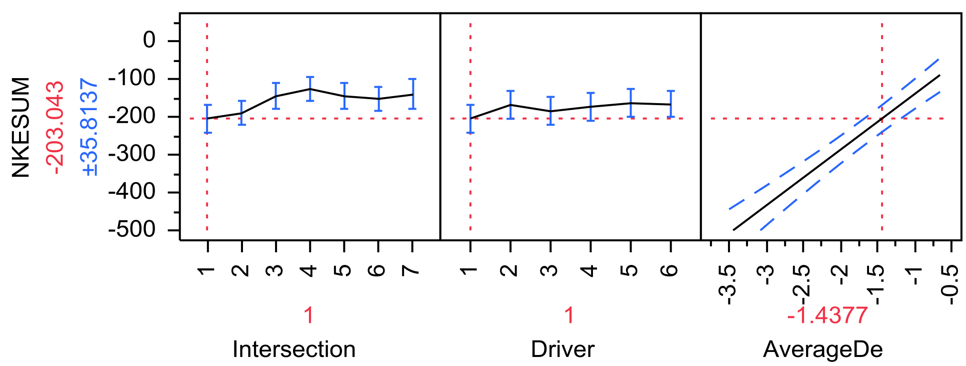
Factor Profiler



NKE Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	82.87931631	21.39283856	3.87	0.0001
Driver1	-27.3242866	11.30034572	-2.42	0.0164
Intersection1	-46.47307909	13.44841629	-3.46	0.0007
Intersection2	-32.81938338	11.28518228	-2.91	0.004
Intersection4	31.71596729	12.38774948	2.56	0.0111
ACC	147.5446131	14.39234151	10.25	<.0001
R-Square	0.447			
Rsquare Adj	0.417			
RMSE	77.836			
Observations	240			
Model F-Statistic	<0.0001*			

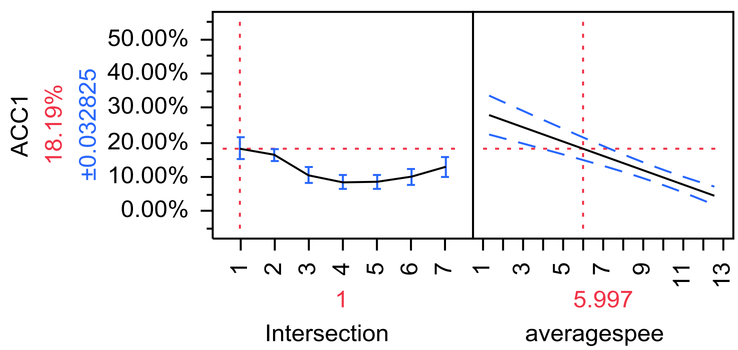
Factor Profiler



ACC1 Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.246471447	0.019320884	12.76	<.0001
Intersection ID[1]	0.060217866	0.01537662	3.92	0.0001
Intersection ID[2]	0.042756866	0.009018101	4.74	<.0001
Intersection ID[4]	-0.037364678	0.010178544	-3.67	0.0003
Intersection ID[5]	-0.035661065	0.009938846	-3.59	0.0004
averagespeed	-0.020806322	0.002996998	-6.94	<.0001
R-Square	0.331417656			
Rsquare Adj	0.311244913			
RMSE	0.061743459			
Observations	240			
Model F-Statistic	<0.0001*			

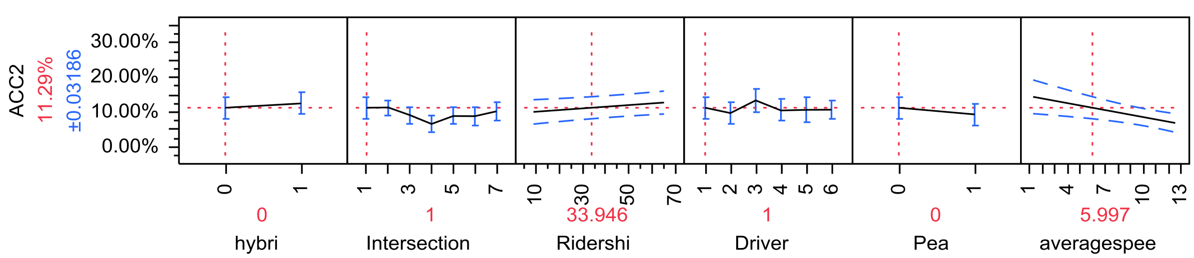
Factor Profiler



ACC2 Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.113046282	0.01829577	6.18	<.0001
hybrid[0]	-0.006189138	0.002996874	-2.07	0.0401
Intersection ID[2]	0.018784838	0.006670494	2.82	0.0053
Intersection ID[4]	-0.028809038	0.007711895	-3.74	0.0002
Ridership	0.000481713	0.000229712	2.1	0.0371
Drivers[2]	-0.013125885	0.006930046	-1.89	0.0595
Drivers[3]	0.023499998	0.006867596	3.42	0.0007
Peak[0]	0.009614761	0.003932095	2.45	0.0152
averagespeed	-0.006710587	0.002366686	-2.84	0.005
R-Square	0.211247332			
Rsquare Adj	0.158429073			
RMSE	0.045519863			
Observations	240			
Model F-Statistic	<0.0001*			

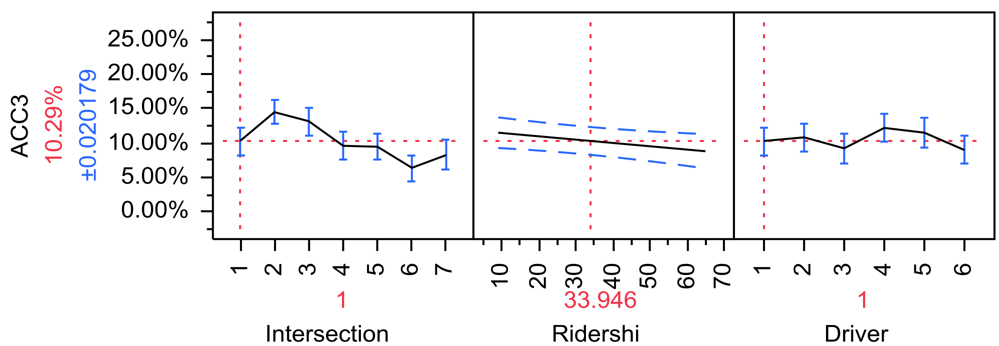
Factor Profiler



ACC3 Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.120650564	0.007943087	15.19	<.0001
Intersection2	0.042404447	0.006365073	6.66	<.0001
Intersection3	0.029245778	0.007073598	4.13	<.0001
Intersection6	-0.038332008	0.006566883	-5.84	<.0001
Driver4	0.016872472	0.006430037	2.62	0.0093
R-Square	0.331			
Rsquare Adj	0.296			
RMSE	0.044			
Observations	240			
Model F-Statistic	<0.0001*			

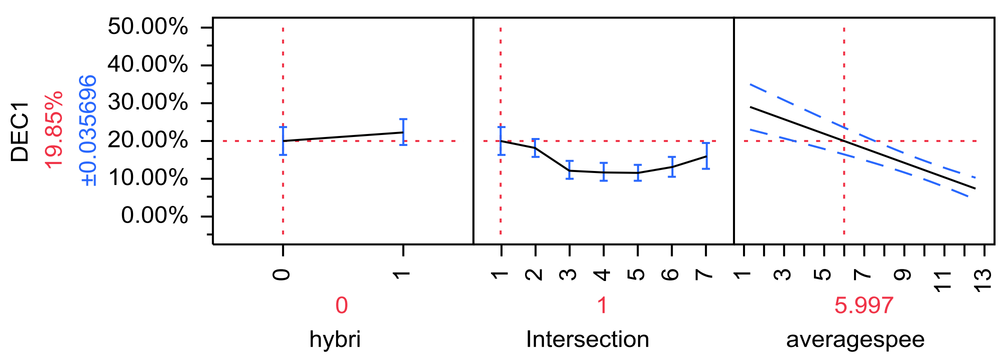
Factor Profiler



DEC1 Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.272027405	0.020418148	13.32	<.0001
hybrid[0]	-0.011364327	0.004235284	-2.68	0.0078
Intersection ID[1]	0.053659729	0.016244195	3.3	0.0011
Intersection ID[2]	0.035247532	0.009527839	3.7	0.0003
Intersection ID[3]	-0.025407734	0.010899405	-2.33	0.0206
Intersection ID[4]	-0.030001943	0.010756104	-2.79	0.0057
Intersection ID[5]	-0.031099462	0.010539659	-2.95	0.0035
averagespeed	-0.019310511	0.003167198	-6.1	<.0001
R-Square	0.289113845			
Rsquare Adj	0.264494411			
RMSE	0.065227068			
Observations	240			
Model F-Statistic	<0.0001*			

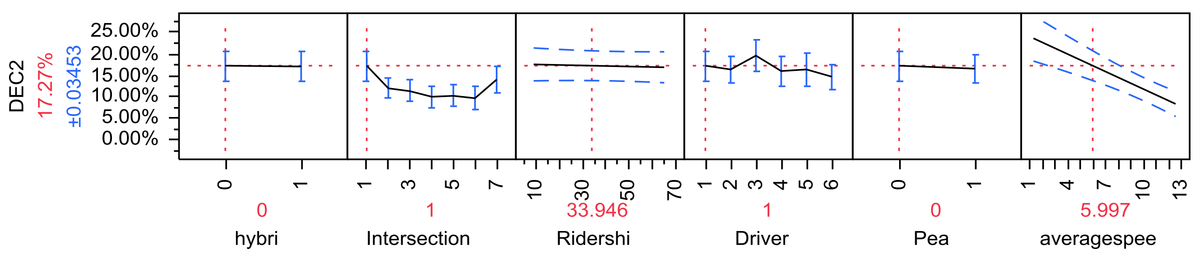
Factor Profiler



DEC2 Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.196524166	0.019829144	9.91	<.0001
Intersection ID[1]	0.051560511	0.012988192	3.97	<.0001
Intersection ID[4]	-0.020398502	0.008358231	-2.44	0.0154
Intersection ID[5]	-0.018312736	0.008008503	-2.29	0.0231
Intersection ID[6]	-0.023839451	0.010255842	-2.32	0.021
Drivers[3]	0.028658147	0.007443171	3.85	0.0002
averagespeed	-0.01351257	0.002565038	-5.27	<.0001
R-Square	0.188366954			
Rsquare Adj	0.134016527			
RMSE	0.049334897			
Observations	240			
Model F-Statistic	<0.0001			

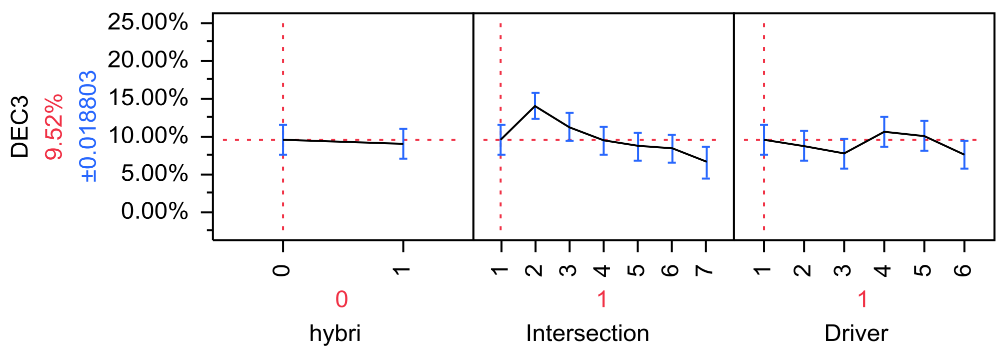
Factor Profiler



DEC3 Regression Model on Campus Route

Parameter	Parameter Estimate	Standard Error of Estimate	t-Value	P(>|t|)
Intercept	0.089109901	0.002650115	33.62	<.0001
Intersection2	0.043030539	0.005754764	7.48	<.0001
Intersection3	0.014851992	0.006396666	2.32	0.0211
Intersection6	-0.013058627	0.005940454	-2.2	0.0289
Driver3	-0.01294931	0.005790771	-2.24	0.0263
Driver4	0.015761819	0.005806622	2.71	0.0071
R-Square	0.29			
Rsquare Adj	0.253			
RMSE	0.04			
Observations	240			
Model F-Statistic	<0.0001*			

Factor Profiler



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