ADVANCES IN VEHICLE EMISSIONS MODELING:
DEVELOPMENT OF A METHODOLOGY FOR THE
KINEMATIC ACQUISITION OF ROADWAY GRADE DATA

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The Academic Faculty

by
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ADVANCES IN VEHICLE EMISSIONS MODELING:
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KINEMATIC ACQUISITION OF ROADWAY GRADE DATA

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DEDICATION

To my family for everything
ACKNOWLEDGEMENTS

Though doctoral work has always carried a deserved reputation for being a rather lonely endeavor, few people, if any, have actually accomplished it alone. In this I have fortunately not been the exception. I had the steady support of many people who sacrificed much to see me through this journey. I wish to thank members of my dissertation committee all of whom were readily available to guide and give insightful advise. I will specifically mention Randy and Wayne for giving me the opportunity to play a major role in significant research, and for pushing me over every obstacle.

To friends, colleagues, and fellow students in TREC lab of old, I cannot thank you enough; your willingness to help in every little way is much appreciated. Finally, I wish to thank members of my family who have been patient and supportive of my quest to go all the way. I have been gone for long but I am now back.
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SUMMARY

Two vehicle emission models, MOBILE and EMFAC, are currently mandated for air quality analysis by the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB), respectively. A major shortcoming with the models is the non-inclusion of roadway geometric characteristics, particularly the road grade, in the model algorithms. Road grade is important for two main reasons: its effect on vehicle activity, and its impact on vehicle emission rates. In the continuing revisions of the models both the EPA and CARB have not yet included a road grade correction factor. One reason for this is the current lack of a cost-effective method to map the grade on millions of miles of roads in the country.

This research addressed this problem by developing a cost-effective methodology to measure roadway grade in kinematic mode. Specifically, a hardware system comprising a fiber-optic gyroscope, a global positioning system (GPS) receiver, and a data-logging computer was designed. The components were integrated with appropriate software programs such that when mounted in a moving vehicle the gyroscope output measures the roadway grade and the GPS receiver output gives the spatial (latitude, longitude) location associated with each grade value. The spatial resolution of the grade data is sufficiently small for the data to be employed in the emerging GIS-based vehicle emission models for project-level air quality analysis.
Because of the errors inherent in the gyroscope output, a linear regression utilizing ordinary least squares procedures was used to develop a calibration model for the gyroscope data. The gyroscope output showed a difference on positive and negative grades; this was attributed to the unequally deflection of the vehicle suspension on the two grade types. As a result, an indicator variable was used in the model specification to differentiate between positive and negative gyroscope reading, and effectively model each separately. The calibration model was used to convert the raw gyroscope readings to actual road grade values. Based on validation tests, the methodology was shown to be consistent and repeatable.

The methodology was used to map the grade on some major roads in the Atlanta region and a GIS-based grade database was developed for these roads. Continuing research on Georgia Tech’s GIS-based vehicle emission model – MEASURE – would use the grade database in the estimation of vehicle emissions for the Atlanta region, and assess the effect of incorporating roadway grade in its algorithm.
CHAPTER 1

INTRODUCTION

1.1 Deficiencies in Current Vehicle Emissions Modeling Procedure

The current vehicle emissions models, MOBILE and EMFAC, mandated by the U.S. Environmental Protection Agency (USEPA) and the California Air Resources Board (CARB), respectively, use fleet average emission rates determined from laboratory tests of vehicles operating under standard conditions. However, because the standard laboratory conditions are not representative of real world vehicle operating conditions, the reliability of outputs from emission models have been widely disputed.

Over the years researchers have identified and documented several deficiencies with the two models (GAO, 1997; Bishop et al., 1996; Washington and Guensler, 1994). As a result of the deficiencies there is significant discrepancy between the modeled outputs and values obtained from field measurements of ambient pollutant concentration (Pierson et al., 1996). Continuing revisions of the models\(^1\) have addressed some of the major issues, but considerable problems still exist. One primary deficiency of the models is that

\(^1\) MOBILE5a, issued in March 1993, is the current version of the MOBILE model that the states are required to use; EPA issued an update version, MOBILE5b, in September 1996 as an option for the states to use in calculating selected emissions reduction credits. A comprehensive revised version, MOBILE6, is slated for release in 2001. EMFAC7F is the current version of CARB's EMFAC model for use in California.
the driving cycles used to develop the models do not adequately reflect real-world driving conditions (Austin et al., 1993). Actual on-road driving conditions and behavior differ significantly from the baseline Federal Test Procedure (FTP) driving cycles. For example, the FTP cycles do not capture the full range of speed, acceleration, and aggressive driving behavior encountered in real life. Other studies have shown that a small proportion of the vehicle fleet may be responsible for a disproportionate amount of pollution emission; these *super emitters* are poorly represented in the models.

Current uses of the MOBILE model range from macroscale to microscale projects and policy evaluation. However the original goal of the model was relatively modest: to model motor vehicle emissions on a county-wide basis for an “average annual day” (Maldonado et al., 1994). Both data and computer hardware limitations resulted in the original model treating data in an aggregated fashion. Thus, early versions of the model were recognized as being relatively rough approximations of real world emissions and, as a result, made use of convenient, readily available parameters such as FTP defined processes. But the continuing need to model activity- and project-specific events has reached the point where the model is no longer considered adequate to supply accurate emission factors in all cases, particularly in modeling microscale projects associated with congestion mitigation and air quality improvement measures.

The use of travel demand models (TDM) to determine vehicle activity poses yet another source of error in the modeling process. Historically, the primary goal of TDMs was to
forecast traffic volumes as a basis for determining the appropriate size (number of lanes) for new and reconstructed highways. Current uses of emissions models require emission producing vehicle activities to be estimated to capture their distribution in different forms and at increasingly smaller scales. But the TDMs are not calibrated to give outputs in such forms or at such scales, and are thus generally insensitive to emission generating activities. Their suitability to supply vehicle activity for emissions models is therefore problematic.

Lastly, and bearing directly on the motivation for this research, is that the modeling procedure does not address the effect of roadway geometric characteristics. In particular, the emission models do not account for the effect of roadway grade on vehicle emissions production. The lack of a roadway grade factor in the FTP testing procedure has been identified as a major source of model misrepresentation (Cicero-Fernandez, 1999).

1.2 Need to Incorporate Grade Effects in Vehicle Emissions Models

The effect of road grade on vehicle emissions has been the focus of several research efforts (Pierson et al, 1996; Cicero-Fernandez, 1999). In modeling vehicle emissions production, road grade is important for two main reasons:

1. its effect on vehicle activity, and

2. its impact on vehicle emission rates.
Road grade impacts vehicle emissions rate by imposing additional gravity load on the engine. The extra load is calculated as the sine of the angle of grade times the vehicle weight (see Section 2.8 and Section 2.9 for a full treatment of this topic). The extra power needed to overcome this load and maintain the same speed is supplied from additional fuel combustion. On a positive grade, vehicles are slowed down as a result of the induced gravity load on the engine; this is especially the case with trucks, buses, and other heavy vehicles on severe positive grades. And on negative grades drivers employ the brakes to maintain speed and control, and this impacts the frequency and duration of acceleration / deceleration and its distribution within the vehicular fleet on a given road link. Depending on the severity of the grade, these effects may play critical roles in the vehicle emissions characterization. A detailed treatment of the effects of roadway grade on engine load and emissions is presented in Section 2.8.

1.3 Research Problem Statement

The foregoing has established the need to include the effect of roadway grade in vehicle emissions models. However, the latest revision to the MOBILE model by the USEPA did not address this deficiency. The major reason attributed for the non-incorporation of a grade factor in the model was identified as the non-availability of roadway grade data on the nations road network (GAO, 1998). This, in turn, was attributed to the non-availability of a cost-effective methodology for collecting the road grade data (GAO, 1998). It can therefore be adduced that by developing such a methodology, and enabling
the development of roadway grade databases, future revisions of the models can finally have the needed data to incorporate a grade factor.

1.4 Research Goal

The goal of this research is to develop a methodology to measure roadway grade in kinematic mode at such spatial resolution that the data can be utilized in emerging GIS-based modal emissions model. It is hypothesized that the output from a fiber-optic electronic gyroscope can be statistically calibrated and modeled to give a consistent and repeatable measurement of roadway grade. The gyroscope output will be integrated with the output from a Global Positioning System receiver that establishes the unique coordinate of each grade output at the needed spatial resolution. The final result will establish a database of linear sequence of points along a given road link, identified by unique \( x \) and \( y \) (longitude and latitude) coordinates, and the associated grade value.

1.5 Summary of Research Contributions

This dissertation presents the results of a study aimed at developing a methodology to measure roadway grade data. Primarily, the availability of roadway grade data will enable the incorporation of grade factors in vehicle emissions models, and further enhance the accuracy of the model output. While research has established a link between high roadway grade and increased vehicle emissions production, the actual relationship is
still uncertain (GAO, 1998). The methodology developed in this research can facilitate research into on-road determination of the threshold value where the road grade becomes an important emissions contributor. The ultimate impact will be the development of adjustment factors for the effect of road grade in emissions models and a better representation of real world conditions in such models.

1.6 Organization of Thesis

This thesis is organized as follows:

The policy and technical background materials leading up to this study are presented in Chapter Two. The problem of air pollution and the contribution of vehicle emissions to it are discussed. The shortcomings in current vehicle emissions models and the need to account for roadway grade in the models are discussed. The presentation also includes an examination of the theoretical underpinning of the relationship between steeper roadway grade and higher vehicle emissions. The different methods of collecting roadway grade data and their shortcomings are discussed; some of the materials are used to establish the motivation and usefulness of this study.

Chapter Three outlines the research framework; it identifies the problem and presents the hypothesis on which this study is based. It also establishes the goals of the study and the
methodology by which the study was carried out. In fact this chapter elaborates further on what this research is about and why it is important.

Chapter Four is titled "Research Procedure" and it describes the activities and methodology adopted to achieve the research goal. It gives detailed description of the equipment and instrumentation, and the method of data acquisition. A discussion of the theory of the fiber optic gyroscope, and that of the global positioning system is given as a prelude for their utilization in the research.

Chapter Five focuses on the analysis and development of a calibration model for the gyroscope output. It formally presents the theoretical statistical model proposed for the gyroscope data and describes the statistical methods employed in the data analysis, as well as justification for the methods employed.

Chapter Six presents the field implementation of the road grade acquisition methodology developed in this research. Step-by-step procedures are described with instructions for proper field practices for a reliable result.

Chapter Seven presents the conclusions that can be drawn from this study, and recommendations for further research.
CHAPTER II

BACKGROUND

2.1 The Air Pollution Problem

Air pollution refers to the presence in the air of toxic or hazardous substances in concentrations and over such duration as to adversely affect life or the environment. The term spans a wide range of spatial and temporal scales, ranging from local to global. While a large fraction of some air pollutants occur as a result of natural processes, human activities contribute significantly to high ground-level concentration of pollutants, especially in the urban areas (FHWA, 1998).

2.2 Air Pollution Standards

In 1970 Congress passed the National Environmental Policy Act (NEPA) which paved way for the establishment of the U.S. Environmental Protection Agency (EPA). In particular, the EPA under the Clean Air Act Amendment of 1970 was empowered to establish a National Ambient Air Quality Standards (NAAQS), and to develop emission standards for cars, trucks, and buses. The states were charged with the task of complying with the NAAQS by developing and implementing State Implementation Plans (SIP) that would demonstrate their control strategy. Pursuant to this, EPA has established standards
for the following pollutants\(^1\): carbon monoxide (CO\(_2\)), oxides of nitrogen (NO\(_x\)), volatile organic compounds (VOC), sulfur dioxide (SO\(_2\)), Ozone (O\(_3\)), lead (Pb), and particulate matter (PM-10 and PM-2.5)\(^2\). The EPA undertakes a periodic revision of the standards (the latest being in July 1997) based on up-to-date scientific understanding of the effects of each pollutant.

Determination of compliance with the NAAQS is based on the results of ambient monitoring, scientific analyses, and empirical modeling. Metropolitan areas that do not meet the standards are termed non-attainment areas and are classified according to the degree of non-compliance with the NAAQS as: severe, serious, moderate, or marginal, in descending order. Table 2-1 lists the current national ambient air quality standards for each pollutant in terms of the level and the averaging times used to evaluate compliance. Figure 2-1 shows locations in the country that do not meet the standard for at least one criteria pollutant as of September 1999, and Figure 2-2 shows classified ozone non-attainment areas as of July, 1999 (EPA, 2000). It is estimated that about one in five people in the US lives in an area that does not meet the standards in at least one of the criteria pollutants (EPA, 1998).

\(^1\) The standards are based on established criteria for risk to human health and/or environmental degradation, hence the pollutants are called “criteria pollutants”. The standards are classified as primary (for the protection of human health), or secondary (for protection against environmental degradation).

\(^2\) PM-10 and PM-2.5 refer to particulate matter with aerodynamic diameter less than 10 and 2.5 microns, respectively.
<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Primary Standard (Health Related)</th>
<th>Secondary Standard (Welfare Related)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type of Average</td>
<td>Standard Level Concentration</td>
</tr>
<tr>
<td>CO</td>
<td>8-hour&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9 ppm (10 mg/m³)</td>
</tr>
<tr>
<td></td>
<td>1-hour&lt;sup&gt;b&lt;/sup&gt;</td>
<td>35 ppm (40 mg/m³)</td>
</tr>
<tr>
<td>Pb</td>
<td>Maximum Quarterly Average</td>
<td>1.5 µg/m³</td>
</tr>
<tr>
<td>NO₂</td>
<td>Annual Arithmetic Mean</td>
<td>0.063 ppm (100 µg/m³)</td>
</tr>
<tr>
<td>O₃</td>
<td>Maximum Daily 1-hour Average&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.12 ppm (235 µg/m³)</td>
</tr>
<tr>
<td></td>
<td>4&lt;sup&gt;th&lt;/sup&gt; Maximum Daily 8-hour Average</td>
<td>0.08 ppm (157 µg/m³)</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>Annual Arithmetic Mean</td>
<td>50 µg/m³</td>
</tr>
<tr>
<td></td>
<td>24-hour Mean&lt;sup&gt;b&lt;/sup&gt;</td>
<td>150 µg/m³</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>Annual Arithmetic Mean&lt;sup&gt;e&lt;/sup&gt;</td>
<td>15 µg/m³</td>
</tr>
<tr>
<td></td>
<td>24-hour Mean&lt;sup&gt;f&lt;/sup&gt;</td>
<td>85 µg/m³</td>
</tr>
<tr>
<td>SO₂</td>
<td>Annual Arithmetic Mean</td>
<td>0.03 ppm (80 µg/m³)</td>
</tr>
<tr>
<td></td>
<td>24-hour Mean&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.14 ppm (365 µg/m³)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Parenthetical value is an approximate equivalent value (see 40 CFR Part 50)

<sup>b</sup> Not to be exceeded once per year

<sup>c</sup> The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm is equal to or less than one as determined according to appendix H of the Ozone NAAQS.

<sup>d</sup> Three-year average of the annual 4<sup>th</sup> highest daily maximum 8-hour average concentration.

<sup>e</sup> Spatially averaged over designated monitors.

<sup>f</sup> The form is the 98<sup>th</sup> percentile.
Figure 2-1: Location of Nonattainment Areas for Criteria Pollutants as of September, 1999 (Adapted from EPA, 2000).

Note: Unclassified areas are not shown.

Figure 2-2: Classified Ozone Nonattainment Areas where 1-hour Standard Still Applies as of July, 1999 (Adapted from EPA, 2000).

Note: Unclassified areas are not shown.
2.3 Automobile Exhaust Emission Standards

New vehicles sold in the US have been subject to increasingly stringent emissions control requirements since the early 1960s. Exhaust emissions standards for cars and trucks under 6000 lb. gross vehicle weight first came into effect in the 1966 model year in California and in the 1968 model year nationwide. Regulations require emission certification by manufacturers prior to introducing vehicles into commerce, and in-use compliance to assure that the standards continue to be met for the useful life of the vehicles. Certification is granted annually to individual engine families and is good for one model year. An engine family is a grouping of vehicles or engine models that exhibit similar emission characteristics (e.g., common engine parameters, fuel system, and emission control systems). The EPA or its designated agency (e.g. CARB for California) enforces the standards.

The standards and the test procedures for certification have changed considerably over the years. The first comprehensive vehicle exhaust standards were introduced in 1970 (the Tier 0 standards) but were not implemented until later. Following this, the 1970s were marked by conflicts between the USEPA and the automobile manufacturers who feared that the emissions regulations were not achievable with existing technology. With some compromise, mainly in the phase-in schedule of the standards, the manufacturers did develop the appropriate technology. The Clean Air Act Amendment of 1990 further tightened exhaust emissions and the EPA instituted more stringent standards and corresponding test procedures (the Tier 1 standards) to replace the Tier 0 standards.
Table 2-2 and Table 2-3, respectively, show the Tier 0 and Tier 1 exhaust emission standards. Phasing in the Tier 1 vehicles began in 1994 and ended with 100% of new vehicle fleet achieving the lower emissions requirement by the year 1999. Requirements for supplemental FTP tests for high engine loads begins with the 2000 model year with 100% compliance expected by the year 2003. The Low Emission Vehicle (LEV) and the Ultra-low Emission Vehicle (ULEV) programs being phased-in in California promise to further tighten new car exhaust emission standards in the future.

2.4 National Air Quality Trend

In its latest report, the USEPA Office of Air Quality Planning and Standards which monitors the national air quality trend, reported a general decline in the emission of all criteria pollutants from their peak in the 1970s to the 1990s as illustrated in Figure 2-3 and Figure 2-4. More emission reduction was recorded from on-road sources than from non-transport sources. In fact today’s new vehicles are 70% to 90% less polluting than those manufactured in the base year of 1970 when Tier 0 standards were introduced. This has been achieved through a combination of regulatory initiatives and technology improvements. Stricter new vehicle tailpipe standards, improved engine and emissions controls, aggressive inspection-maintenance programs, cleaner burning fuels, and durability requirements for emissions controls have all combined to significantly reduce vehicle tailpipe emissions.
Table 2-2:  Tier 0 Certification Exhaust Emission Standards (Federal)$^1$

<table>
<thead>
<tr>
<th>Vehicle Category</th>
<th>THC g/mi</th>
<th>NMHC g/mi</th>
<th>CO g/mi</th>
<th>NO$_x$ g/mi</th>
<th>PM$_{10}$ g/mi</th>
<th>HCHO Mg/mi</th>
<th>Useful Life (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>0.41</td>
<td>---</td>
<td>3.4</td>
<td>1.0</td>
<td>0.20</td>
<td>---</td>
<td>50K</td>
</tr>
<tr>
<td>LDT1</td>
<td>0.80</td>
<td>---</td>
<td>10</td>
<td>1.2</td>
<td>0.26</td>
<td>---</td>
<td>120K</td>
</tr>
<tr>
<td>LDT2,3,4</td>
<td>0.80</td>
<td>---</td>
<td>10</td>
<td>1.7</td>
<td>0.13</td>
<td>---</td>
<td>120K</td>
</tr>
</tbody>
</table>

Table 2-3:  Tier 1 Certification Exhaust Emission Standards (Federal)$^1$

<table>
<thead>
<tr>
<th>Vehicle Category</th>
<th>THC g/mi</th>
<th>NMHC g/mi</th>
<th>CO g/mi</th>
<th>NO$_x$ g/mi</th>
<th>PM$_{10}$ g/mi</th>
<th>HCHO Mg/mi</th>
<th>Useful Life (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV, LDT1</td>
<td>0.41 ($^6$)</td>
<td>0.25 (0.31)</td>
<td>3.4 (4.2)</td>
<td>0.4 (0.6)</td>
<td>0.08 (0.10)</td>
<td>---</td>
<td>100K</td>
</tr>
<tr>
<td>LDT2</td>
<td>--- (0.80)</td>
<td>0.32 (0.40)</td>
<td>4.4 (5.5)</td>
<td>0.7 (0.97)</td>
<td>0.08 (0.10)</td>
<td>---</td>
<td>100K</td>
</tr>
<tr>
<td>LDT3</td>
<td>--- (0.80)</td>
<td>0.32 (0.46)</td>
<td>4.4 (6.4)</td>
<td>0.7 (0.98)</td>
<td>---</td>
<td>---</td>
<td>120K</td>
</tr>
<tr>
<td>LDT4</td>
<td>--- (0.80)</td>
<td>0.39 (0.56)</td>
<td>5.0 (7.3)</td>
<td>1.1 (1.53)</td>
<td>---</td>
<td>---</td>
<td>120K</td>
</tr>
</tbody>
</table>

$^1$ Adopted from Chrysler (1998).
Standards in parenthesis are useful life standards; other standards are for 50K miles.
See Descriptions for the meanings of the various vehicle category.
Figure 2-3: Long Term Trend in National Emissions of SO₂, NOₓ, VOC, and PM₁₀ - excluding Fugitive Dust Sources. (EPA, 1996).

Figure 2-4: Long Term Trend in National Emissions of CO, Pb, and PM₁₀ - from Fugitive Dust Sources (EPA, 1996).
In spite of the general trend, however, the air quality improvements that were anticipated when tailpipe standards were introduced have not been fully achieved. Figure 2-5 shows the percentage contributions to the national inventory of CO, NOx, and anthropogenic VOC by major source category; as can be seen here, the transportation sector (which includes all on- and off-road vehicles) continues to be a major contributor to all three. Air pollution still is a major problem in most urban areas with an estimated 102 million people living in areas that are in violation of the revised standards for ozone (EPA, 1998). Increasing population and dispersed activity patterns continue to necessitate automobile use so that the tremendous gains made in engine and fuel efficiency are being offset by increasing vehicle miles traveled and an exploding vehicle ownership rate, as shown in Figure 2-6 and Figure 2-7, respectively. Between 1970 and 1995, fuel use increased approximately 50% and vehicle miles traveled (VMT) increased over 100%. These trends in travel demand threaten to reverse the gains made through increased technical and regulatory standards.

In 1998 the transportation sector contributed more than 78% of the total CO, 53% of the NOx, and 43% of anthropogenic VOC. Unfortunately, this trend is projected to continue in the future (as illustrated in Figure 2-8) as vehicle ownership and VMT continue to rise. In characterizing the nation’s ten-year air quality trend between 1989 and 1998, the EPA stated that 21 metropolitan areas had statistically significant upward trend in ambient concentrations for at least one criteria pollutant, while 221 areas had statistically significant downward trend for at least one criteria pollutant. However, the Air Quality
Figure 2-5: National Emissions of CO, NOₓ, and Anthropogenic VOC by Major Source Category in 1998 (EPA, 2000).

(a) CO Emissions:

(b) NOₓ Emissions:

(c) Anthropogenic VOC Emissions:
Figure 2-6: National Trend in Vehicle Miles Traveled (AAMA, 1993)

Figure 2-7: National Trend in Vehicle Ownership (AAMA, 1993)

Figure 2-8: Projected Contribution of the Transportation Sector to US Emissions (EPA, 1997)
Quality Index (AQI) analysis of the 94 largest metropolitan areas in the nation showed that in the same period the total number of “unhealthy” days decreased an average of 57% in Southern California but increased 10% in the rest of the major cities across the country (EPA, 2000). Thus, while the national trend is encouraging the EPA has stated that further restrictions on vehicle emissions is still necessary to attain the desired levels of ambient air quality.

2.5 The Automobile and Air Pollution

The link between automobile emissions and air pollution attracted little attention before the 1950s. Through studies in the Los Angeles area, where the peculiar circumstance of topography, local meteorological conditions, and high automobile volume created an acute smog problem, it became clear that automobiles were a major source of urban air pollution (Horowitz, 1982). Motor vehicle emissions contribute directly to four of the six criteria pollutants listed in Table 1-1: CO, NOx, VOC, and PM10. Through complex photo-chemical reactions involving VOCs and NOx that produce O3, vehicle emissions are also indirectly linked to ground level ozone (Hochgreb, 1998; Guensler, 2000).

2.5.1 The Internal Combustion (IC) Engine

By far the predominant engine design for transportation vehicles is the reciprocating internal combustion (IC) engine which operates either on a four-stroke or a two-stroke cycle. The two-stroke engine is used for small passenger cars, motor cycles, and
outboard marine engines, while the four-stroke engine is most commonly used for road vehicles such as cars and light duty trucks. To understand the formation and control of emissions, it is necessary to have an understanding of the operation of the internal combustion engine.

Internal combustion engines generate power by converting the chemical energy stored in fuels into mechanical energy. The engine is termed "internal combustion" because the chemical energy is released by burning the fuel inside the engine to produce heat energy. Conversion of heat energy to mechanical energy is accomplished by allowing the heat energy to act on a medium, causing its pressure to increase and performing work as the medium expands.

In the four-stroke engine cycle (also called Otto cycle) the following processes take place during one cycle of operation:

1. **Intake (or induction) stroke**: charging the cylinder with a fresh charge composed of a mixture of fuel and air (for spark-ignition or gasoline engine) or air only (for auto-ignition or diesel engine). This mixture is commonly termed air/fuel mixture or simply charge.

2. **Compression stroke**: compression of the charge to a temperature suitable for combustion. In gasoline engines combustion is started by ignition from a spark plug; in diesel engines auto-ignition occurs when fuel is
injected into the compressed air which temperature is high enough to cause self-ignition.

3. **Expansion (or power) stroke:** expansion of the high pressure gases as the charge mixture burns. The combustion process results in a substantial increase in the gas temperature and pressure.

4. **Exhaust stroke:** discharge of the burnt gases (exhaust) from the cylinder to make room for a fresh charge of the next cycle.

Fig. 2-9 is a diagrammatic representation of the four strokes of an internal combustion engine. The usual form of converting the work performed by the expanding medium into useful mechanical work is by combusting the fuel in a **cylinder** in which a sliding **piston** is free to move at the bottom end. The upper end of the cylinder consists of a clearance space in which ignition and combustion occur. The expanding medium pushes against the piston, causing it to move; this straight line motion of the piston is converted into the desired rotary motion of the wheels by means of a **drivetrain** consisting of a **connecting rod** and **crankshaft**. The air/fuel mixture preparation is done through **carburetion** or **fuel injection**, and the exhaust gases are passed to the atmosphere through the **exhaust** system.

It can be seen from Figure 2-9 that the only stroke that delivers useful work is the expansion stroke; thus the other three strokes are termed idle strokes. The reader interested in a detailed description of the internal combustion engine is referred to specialized texts such as Heywood (1988) and Newton et al. (1996).
Figure 2-9: The Actions of a Four-Stroke Internal Combustion Engine
(Adapted from Heywood, 1988)
2.5.2 Mechanism of Vehicle Emissions Formation

Emissions from vehicle engines arise from three sources: the crankcase, the fuel system, and the exhaust. During the compression and power strokes some of the gases in the cylinders escape past the pistons and into the crankcase; this is crankcase or blowby emissions and consist mostly of unburned / partly burned air-fuel mixture with high VOC content. Emissions from the fuel system are caused by evaporation from the carburetor and tank as a result of gradual heating of the engine. This consists of VOC, and also occur on warm days even with the vehicle not in use (diurnal emission). Exhaust emissions result from the incomplete combustion of the fuel mixture residue discharged into the atmosphere during the exhaust stroke; this accounts for all CO, NOx, and some of the VOC emissions.

If the fuel supplied to the cylinders burned completely, then it would be oxidized to carbon dioxide and water. This happens when just enough oxygen is available to combust all the hydrocarbon. Such perfect and complete combustion is called stoichiometric and, for a variety of reasons, is seldom attained in internal combustion engines. The reasons include excessive supply of oxygen (lean condition); inadequate supply of oxygen (enriched condition); incomplete hydrocarbon combustion from transient conditions such as cold start, idling, and acceleration / deceleration; inadequate charge atomization; wall quenching; and engine malfunctions or maladjustments. In reality, since combustion conditions in an internal combustion engine are not ideal, complete oxidation does not occur even when the mixture is stoichiometric.
Enriched conditions occur when the air-fuel charge contains less amount of oxygen than stoichiometric, and thus not enough is available to combust all of the hydrocarbons. The unburned and partially burned hydrocarbons get into the exhaust stream as VOC’s and CO. Lean conditions occur when more oxygen than stoichiometric is available. At high engine temperatures the excess oxygen react with nitrogen in the air mixture to form nitrogen oxides.

2.5.3 Control of Vehicle Emissions

Control of vehicle emissions employs both regulatory and technical instruments. Most regulatory instruments are technology-forcing, e.g. mandating manufacturers to meet certain design standards. On the technical side, there are two basic methods used to control vehicle emissions: engine-design measures and exhaust gas treatment.

2.5.3.1 Engine-Design Measures

Vehicle emissions rates are sensitive to a variety of engine adjustments and design parameters, including, air-fuel ratio, spark timing, valve overlap, surface-to-volume ratio, and compression ratio, among others. For a given design, the emissions characteristics of on-road vehicles depend very much on the proper adjustments of engine parameters. In modern engines this is effected through the use of on-board computers with electronic sensors that monitor the state of the engine and conditions in the cylinder to make the appropriate adjustments.
Spark Timing: To achieve maximum power output and fuel economy, it is desirable for the ignition spark to be timed to occur before the piston reaches top-dead-center. This enables combustion to develop in the cylinder before the power stroke begins and maximizes the pressure applied to the piston. The optimal degree of spark advance depends on engine operating conditions such as engine speed and intake manifold pressure, but can be as early as 30° of crankshaft rotation. The trade off is between fuel economy and emissions reduction. It is possible to reduce HC and NOx emissions, at the cost of fuel economy, by retarding the spark; spark retardation reduces the peak combustion temperature and increases the exhaust temperature. The reduced combustion temperature decreases NOx formation, while the increased exhaust temperature enables further oxidation of HC in the exhaust stream. In addition, spark retardation causes the combustion period to extend further into the power stroke, thereby reducing the cylinder's surface-to-volume ratio, which is important in HC emissions. Spark timing has little effect on CO emissions.

Valve Overlap: This refers to a condition in which the intake and exhaust valves of a cylinder are partially open simultaneously. Valve overlap typically occurs between the exhaust and intake strokes of the engine. Since the valves cannot be shut instantaneously, there is an interval before the end of the exhaust stroke and after the beginning of the intake stroke, when both exhaust and intake valves are open. As a result some of the exhaust gases are re-inducted into the cylinder during the intake stroke. The re-inducted gas usually contains much HC which is burned in the subsequent cycle: this reduces HC
emissions. Also, the inert constituents of the re-inducted gas dilute the air-fuel mixture and reduce its peak combustion temperature, thus reducing NOₓ emissions. However a high dilution may inhibit combustion and increase HC emissions, and affect engine efficiency.

Surface-to-Volume Ratio: This refers to the ratio of the surface area of the cylinder walls to the volume of the cylinder. The proportion of air-fuel mixture adjacent to the cylinder walls decreases as the surface-to-volume ratio decreases. Because of the importance of wall quenching in HC emissions, cylinders with relatively low surface-to-volume ratios tend to produce lower HC emissions than those with higher ratios.

Compression Ratio: The compression ratio is the ratio of the full volume of the cylinder with the piston at bottom-dead-center to the volume of the clearance space in the cylinder with the piston at top-dead-center. This ratio is typically between 6 and 9 in most IC engines. Reducing the compression ratio tends to reduce the surface-to-volume ratio and the peak combustion temperature, whereas it tends to increase the exhaust temperature. Therefore reducing the compression ratio tends to reduce HC and NOₓ emissions, but it also tends to reduce thermal efficiency and thus fuel economy.

Air-Fuel Ratio: Perhaps the most important engine parameter in characterizing vehicle emissions is the air-fuel ratio. This refers to the ratio of the mass of air to the mass of fuel in the air-fuel mixture, and is a good indicator of engine operation and emission
composition. An air-fuel ratio of 14.7:1 is the stoichiometric mark in typical internal combustion engines. The effect of air-fuel ratio on emissions is best studied using the air-fuel equivalence ratio $\lambda$, or its reciprocal $\phi$, the fuel-air equivalence ratio; this quantity is defined as:

$$\text{Fuel-air equivalence ratio, } \phi = \frac{\text{[fuel-air ratio]}_{\text{actual}}}{\text{[fuel-air ratio]}_{\text{stoichiometric}}} \quad \text{(2.1)}$$

A fuel-air equivalence ratio of 1.0 indicates stoichiometric conditions; less than 1.0 indicates lean conditions, and more than 1.0 indicates enriched conditions. Figure 2-10 illustrates the variation of pollutant emissions with the fuel-air equivalence ratio. The optimum air-fuel ratio is a direct trade-off between fuel economy, power output, and emissions reduction. In general a mixture 10% richer than stoichiometric gives optimum power at air-fuel ratio of 12.5:1; but optimum fuel efficiency is obtained with a mixture 10% leaner than stoichiometric at air-fuel ratio of 16:1 (Newton et al., 1996). Rich air-fuel mixtures produce high levels of CO and HC because combustion is mostly incomplete. Emissions of HC and CO is reduced by operating with lean mixtures; but this has the disadvantage of reducing engine power output and increasing NO$_x$ emission. If either the flame temperature or burn duration in the cylinder is reduced, the NO$_x$ emissions will also be reduced. Retarding the ignition, and exhaust gas recirculation are also effective NO$_x$ reduction strategies as they lower peak pressure and temperature. But these also have adverse effects on engine power and fuel economy.
Figure 2-10: Representative Trends for the Emissions of CO, NO\textsubscript{x}, and HC with Fuel-Air Equivalence Ratio (Stone, 1993)
The power demanded from a vehicle’s engine is a function of speed, change in speed (acceleration or deceleration), loads (wind resistance, cargo, grade), and operation of accessories (air-conditioning, heating). Because power requirements beyond the battery capacity is produced from the engine, in order to provide sufficient power at the needed speed a rich air-fuel mixture is *commanded* by the on-board computer. This results in elevated levels of HC and CO and reduced fuel efficiency. Quick acceleration and deceleration coupled with operation at high speed (termed *aggressive driving*) will typically result in enrichment emissions than cruise driving. Also the first few minutes of engine operation (termed *cold start*) is accompanied by elevated emissions. This results partly from commanded enrichment to keep the engine from stalling. Emissions from commanded enrichment has been shown to be a significant contributor to overall vehicle emissions (Leblanc et al., 1996). From the foregoing it is clear that the mode of operation (activity) of the vehicle and roadway geometric characteristics are important factors in emissions quantity and characterization.

2.5.3.2 Exhaust Gas Treatment

In addition to engine-design modifications, manufacturers have achieved compliance with emissions standards by installing exhaust gas treatment devices such as *catalytic converters* on new vehicles. Converters consist of catalysts which promote further oxidation / reduction of pollutants in the exhaust stream before it is discharged. Two-way converters were the first in use; the term two-way conversion implies oxidation of the two pollutants HC and CO to form CO₂ and H₂O. The catalysts are noble metals.
such as platinum and palladium which facilitate the oxidation process, and are enclosed in an aluminized steel heat shield. Later on the three-way converter which incorporates NO\textsubscript{x} reduction was introduced. This utilizes a two-stage process with NO\textsubscript{x} reduction taking place in the second stage. The reduction process is catalyzed by rhodium.

The catalysts are more effective at high temperatures and with large surface areas over which the reaction can occur. Thus the catalysts are deposited on a honeycomb structure of metallic or ceramic substrate to provide the needed large surface area while maintaining compactness. In addition to transient engine conditions, cold start engines have high emissions partly because the converter catalysts have not yet attained a high enough temperature to be effective. No meaningful treatment of pollutants takes place until the converter has reached an operating temperature of approximately 250\textdegree\ C; the ideal operating temperature for maximum efficiency and prolonged life is approximately 400 – 800\textdegree\ C. Lead destroys the effectiveness of the catalysts, so catalytic converter equipped vehicles operate exclusively on unleaded gasoline.

Another exhaust gas treatment procedure is the exhaust gas re-circulation (EGR) which has been in use from the 1973 model year. EGR consists of re-circulating a portion of the exhaust gas to the intake manifold. This dilutes the air-fuel mixture, without additional oxygen, and reduces the peak combustion temperature. The combined effect is a reduction in NO\textsubscript{x} emissions.
2.5.3.3 Control of Evaporative Emissions

The earliest vehicle emissions control were for crankcase emissions which were first installed on new vehicles with the 1963 model year. Crankcase emissions result mostly from blow-by gases and is eliminated by closing the crankcase vent to the outside and re-circulating the gases to the intake manifold. This is called positive crankcase ventilation (PCV). Fuel vapor from the carburetor and tank is either re-circulated to the crankcase or stored in a canister from where it is also returned to the intake and burned. In modern vehicles, crankcase emissions have been essentially eliminated. Evaporative emissions are not a problem with diesel engines because of the low volatility of the diesel.

2.6 Modeling of Vehicle Emissions

Vehicle emissions modeling involves two basic steps: in one step the amount of vehicle activity - typically the vehicle miles traveled (VMT) per year - in the area of interest is established, and in the other step the rate of emission production is determined. The emission rates are calculated as a function of the average vehicle speed and expressed as mass of pollutant per unit of vehicle activity. For a given average speed, the total emissions is then calculated as:

\[ \text{Emissions (g)} = \text{vehicle activity (km) } \times \text{ emission factor (g/km)} \]
Vehicle activity is determined using a Travel Demand Forecasting Model (TDM). The travel demand model utilizes several characteristics of the transportation system and socio-economic data to forecast link-specific traffic volumes and average speeds for the entire network.

Emission rate factors are determined from Mobile Source Emission Models such as the MOBILE series. The procedure for determining the emission factors is based in part on a standard test called the Federal Test Procedure (FTP) - see below for a description of the FTP test procedure. From the FTP tests a "base" emission rate for each pollutant is obtained. Adjustments are made to the base emission rates using correction factors developed from an assessment of the local vehicle fleet and road network characteristics, fuel type, environmental factors, and the local vehicle emissions control strategies. The adjusted emission rate is used in the emission relationship given above.

2.6.1 The Federal Test Procedure (FTP)

The Federal Test Procedure is an aggregate of tests that are used to determine vehicle emissions and fuel economy. The test incorporate procedures to measure exhaust, evaporative, and refueling emissions for motor cycles and for three vehicle categories: cars, trucks, and heavy duty trucks. The tests are used to monitor compliance with a number of regulatory requirements. Under EPA regulations, vehicle manufacturers must certify that their products meet new car emissions standards for the criteria pollutants
through prescribed FTP tests. Transportation and air quality agencies employ FTP test procedures in using the MOBILE models for air quality assessments.

The FTP exhaust emission tests are based on the Urban Dynamometer Driving Schedule (UDDS), part of which is also called the Los Angeles Driving Cycle #4, or simply LA4. The original UDDS was developed in the mid 19960's to be representative of a typical urban home-to-work commute for the Los Angeles area. It has since undergone some modifications, and the current UDDS is depicted in Figure 2-11; the cycle consists of three sections reflecting different modes of driving and vehicle operation. During the test, a sample of the vehicle exhaust gas from each section is collected in separate bags, hence the three sections are termed Bag 1, Bag 2, and Bag 3, respectively.

The test starts after the vehicle has been parked for 12-36 hours at a temperature of 20°-30° C to ensure that the engine is cold. The exhaust gas of the first 505 seconds are collected in Bag 1; this represents a cold transient drive. The exhaust gas of the next 866 seconds are collected in Bag 2 to represent a hot stabilized drive. Thereafter, the engine is stopped for 10 minutes (soak) and then restarted. The first 505 seconds after the restart is collected in Bag 3 to represent a hot transient drive. The emissions from Bags 1 and 2 are weighted 0.43 and the emissions from Bags 2 and 3 are weighted 0.57; the weighted total emissions are then adjusted for in-use deterioration to establish the base emission rates. The emissions are measured on a volume basis and converted to grams per mile based on the distance traveled. The test covers a total distance of 11.04 miles.
Figure 2-11: The Federal Test Procedure Driving Cycle
(adapted from Chrysler, 1998)

Federal Test Procedure

<table>
<thead>
<tr>
<th>Test Cycle Portion</th>
<th>Avg Speed</th>
<th>Distance</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP (Entire Cycle)</td>
<td>21.2 mph</td>
<td>11.04 miles</td>
<td>1877 sec.</td>
</tr>
<tr>
<td>LA4 (Bags 1&amp;2)</td>
<td>19.5 mph</td>
<td>7.45 miles</td>
<td>1372 sec.</td>
</tr>
<tr>
<td><em>505</em> (Bag 1 or Bag 3)</td>
<td>25.6 mph</td>
<td>3.59 miles</td>
<td>505 sec.</td>
</tr>
</tbody>
</table>

Max Speed: 56.3 mph
Max Accel: 3.6 mph/sec.
The FTP does not include all in-use driving patterns; the UDDS has maximum speeds of only 56.3 mph and maximum accelerations of 3.6 mph/sec. Real world driving, however, typically involves speeds and accelerations far in excess of these, and the use of vehicle accessories such as heating and air-conditioning. As a result, the EPA has developed two additional tests to simulate these conditions. The additional test cycles are the US06, which simulates high speed and acceleration, and the US03, which simulates air conditioning and accessory use. The two cycles are shown in Figure 2-12 and Figure 2-13, respectively. The inclusion of these two cycles, however, still did not address the effect of roadway grade on vehicle emissions.

2.7 Emerging Mobile Source Emission Models

As a result of the deficiencies in current emissions models, several of which were discussed in Section 1.3, efforts are under way to develop mobile emission models that will address these limitations. Some of these “new generation” models are geared towards providing highly time-resolved emission data suitable to capture vehicle activities by the second. Prominent among these efforts are the model development activities going on at the Georgia Institute of Technology and at the University of California in Riverside.
Figure 2-12: US06 Supplemental Federal Test Procedure Driving Cycle (adapted from Chrysler, 1998)

Figure 2-13: US03 Supplemental Federal Test Procedure Driving Cycle (adapted from Chrysler, 1998)
2.7.1 The Georgia Tech MEASURE Model

The Georgia Tech effort is organized under the auspices of the Georgia Tech Research Partnership, comprising researchers from Georgia Tech, US Environmental Protection Agency - Office of Mobile Sources, Ford Motor Company Research Laboratories, General Motors NAO Research Laboratories, and Georgia Department of Natural Resources. It is aimed at developing a mobile emissions modeling system called the Mobile Emissions Assessment System for Urban and Regional Evaluations (MEASURE). The MEASURE modal emissions model is built upon a geographic information system (GIS) framework (Bachman et al. 1997).

This approach models emission as a function of different engine and vehicle modes of operation that have been found from existing emissions test records to be statistically significant in the emissions formation process. The model incorporates vehicle activity measure (starts, idle, cruise, positive kinetic energy\(^3\) (PKE) acceleration, deceleration), vehicle technology characteristics (model year, engine size, transmission type), and operating conditions (road grade, traffic flow). Vehicle activity measures are presented as percent of cycle time spent in the specified condition; e.g. ACC.3 – percent acceleration greater than 3.0 mph/s, or PKE.60 – percent PKE greater than 60 (mph)\(^2\)/s. The model uses a two-step procedure for emissions estimation: vehicles are first classified to a vehicle technology group, then emission rates are estimated for each technology group. The emission rate estimation methodology is based on a statistical

\(^3\) PKE is the product of instantaneous speed (mph) and acceleration (mph/s).
analysis procedure called hierarchical tree-based regression analysis (HTBR). Tree analysis is a non-parametric technique that iteratively divides a data set into two parts at every juncture by (1) selecting among all the variables offered in the model the one that explains the most variability in the data, and (2) determining the value of the variable that explains the most variability. The end result is a “tree” with “branches” split at “nodes”; each node represents the predictor variable for the condition tested. Adjustments are made to the HTBR estimates for factors not incorporated in the variable set (e.g. vehicle accessory usage).

The records from which the model was developed combined a variety of emission test data sets from different sources to maximize the comprehensiveness of the vehicle fleet and potential operating conditions. The combination of modal classification and a high-resolution GIS framework enables the temporal and spatial allocation of mobile emissions appropriate for regional and project level evaluation. The MEASURE model is made up of 12 modules (Figure 2-14), which can be modified as the need arises (Bachman, 1998).
Figure 2-14: Design of the MEASURE Model (Bachman, 1998)

GIS-Based Model of Automobile Exhaust Emissions

**Input Data:**
- Census Block Data
- Land Use Data
- Traffic Analysis Zone Data
- Vehicle Registration Data
- Road Network Data
- Travel Demand Forecasting Network
- Speed/Acceleration Profiles
- Road Grade Data

**Spatial Environment**
1. Zonal Module
2. Road Module

**Fleet Characteristics**
3. Zonal TG Module
4. On-road TG Module

**Vehicle Activity**
5. Engine Start Activity Module
6. Minor Road Activity Module
7. Running Exhaust Activity Module

**Facility Emission**
8. Engine Start Emissions Module
9. Minor Road Running Exhaust Module
10a. Agg. Modal Running Exhaust Module
10b. SCF Running Exhaust Module

**Emission Inventory**
11. Hourly Gridded Starts, Hot Stabilized, Enrichment, and Total Emissions Module
2.7.2 The UC Riverside Physical Model

The University of California Riverside research team started working in 1995, under sponsorship through the National Cooperative Highway Research Program, to develop a simulation model based on a physical modeling approach (Barth et al. 1996). The modeling approach adopted divides the emission process into different components that can be related to some physical parameters associated with vehicle operation. Since the model is based on such physical interpretations the approach is deterministic and relies on capturing the causal relationships between emission production and various vehicle operation parameters.

In developing the model, data was collected from about 300 vehicles tested on the FTP and other driving cycles. The model is designed to track second-by-second emission data of an individual vehicle as a function of power demand and engine operating status, and to use this to develop emission rates for specific vehicle technology groups. Power demand is predicted from environmental factors (wind resistance, road grade, air density, temperature, and altitude) and vehicle parameters (velocity, acceleration, vehicle mass, cross-sectional area, aerodynamics, accessory load, drive-train and transmission efficiency). The vehicle technology groups include variables of engine type (spark ignition or compression ignition), fuel delivery system (carburetion or fuel injection), emission control system (open-loop or close-loop), and catalyst type (no catalyst, two-way oxidation, or three-way catalyst).
The physical approach relies on second-by-second data based on parameters from individual vehicles. Accurate predictions of these parameters is tantamount to predicting individual driver behavior, among other highly variable data, hence it is likely the activity estimates will have high variability. Bachman (1998) has noted that while aggregating the data to statistical distributions will lessen this problem, it departs from the original model goal of highly time-resolved emission estimates. Hence data input error could significantly degrade the accuracy of the final emission estimates from the model.

The Georgia Tech and UC Riverside modeling philosophies differ fundamentally in that while MEASURE relies on empirical relationships that exhibit statistical significance in an analysis of existing FTP test records, the Riverside physical model is based on causal relationships that require new testing. As vehicle engine technology changes with time, it will be necessary to continually update the technology groupings and run new tests to establish the appropriate estimates for the physical model. Also, for a more accurate application of the model in regional analysis, a representative fleet of the region will be needed for the tests, thus making application of the physical model a more expensive approach. It is important to note that both models have modules that incorporate road grade effects, and this is one area that the result of this research will find application.
2.8 Effect of Roadway Grade on Vehicle Emissions

Roadway geometry is a basic element in the design, maintenance, and improvement of roads. The three basic geometric elements of a roadway are the horizontal alignment, the cross-slope or amount of super-elevation, and the longitudinal profile or grade (Wright, 1996). Of these, the grade has been shown to have significant impact on vehicle emissions (Cicero-Fernandez, 1997a and 1997b; Pierson et al., 1996; Ripberger et al., 1996). It has also been estimated that about 6% of vehicle miles traveled (VMT) nationwide occur on roadways with grades of 4.0% or higher (EPA, 1980). In the modeling process, roadway grade is important for two main reasons: its effect on vehicle activity, and its effect on vehicle emissions rates (Grant, 1998).

2.8.1 Effect of Grade on Modal Activity

The effect of grade on modal activity has long been recognized in the highway design field. In the operational analysis of basic freeway segments, the Highway Capacity Manual requires such analysis to be divided into segments of road differentiated by the severity of the road grade (TRB, 1998). Another text, A Policy on Geometric Design of Highways and Streets (AASHTO, 1994) provides extensive guidelines on the geometric design of highways and other road facilities. These texts recognize the effects of grade on the efficient operation of roadways, and provide specific design considerations for them. On a positive grade, vehicles are slowed down as a result of the grade-induced gravity load; this is especially so with trucks, buses, and other heavy vehicles on severe grades. On negative grades most drivers use their brakes to maintain speed and control of
speed and control of the vehicle. Thus road grade, in this manner, impacts the frequency and duration of acceleration / deceleration and its distribution within the vehicle fleet on a given road link.

2.8.2 Effect of Grade on Emission Rate

A number of studies have been conducted to help characterize the effects of roadway grade on emissions. No quantitative conclusions have yet been reached and there is still uncertainty about the exact relationship (GAO, 1997). However, the general findings from the literature (Cicero-Fernandez and Long, 1995; Pierson et al., 1996) suggest that steeper road grade exacerbates vehicle emissions.

Road grade impacts vehicle emissions rate by imposing additional gravity load on the engine. The extra power needed to overcome this load and maintain the same speed is supplied from additional fuel combustion. The vehicle’s control unit responds to this by enriching the charge mixture, thus elevating HC and CO formation. Thus, the basic effect of grade on emission is similar to and explained by commanded enrichment.

2.8.3 Research into the Effect of Grade on Emissions

2.8.3.1 Tunnel Studies

An initial tunnel study was conducted in 1987 in the Van Nuys Tunnel (CA) to verify the emissions inventory in Southern California. The results showed that measured CO and HC levels in the tunnel were higher than predicted by the EMFAC7C model by factors of
3 and 4, respectively (Ingalls et al., 1989). Several published reports before and since have documented discrepancies in modeled and field-measured pollutant inventories. In 1992 the Desert Research Institute, as part of the Southern Oxidants Study, undertook tunnel studies in Maryland and Pennsylvania to provide real-world emissions data for comparison with MOBILE output. Using a mass flow methodology, vehicle pollutants emission rates were measured in the Fort McHenry Tunnel and in the Tuscarora Mountain Tunnel. The results were published in a series of articles and in a final report (Robinson et al., 1994; Pierson et al., 1996; Gertler et al., 1997).

The Fort McHenry tunnel carries I-95 east-west underneath Baltimore harbor; it has downgrades and upgrades reaching from \(-3.76\%\) to \(+3.76\%\), with no significant level portions. The average grade from west portal to bottom is \(-1.8\%\), and from bottom to east portal is \(+3.3\%\). The Tuscarora Mountain Tunnel is part of I-76 east-west through the Tuscarora Mountain in south central Pennsylvania; the vertical profile is flat, with a grade of only \(0.30\%\) towards the middle from either end, and straight.

Part of their results showed that the effect of grade on emissions rates is significant; more so on the upgrade than downgrade, and for heavy duty vehicles than for light duty vehicles. In general, emission rates upgrade (grades 0.0\% to \(+3.76\%\), average \(3.30\%\)) were double the emission rates downgrade (grades 0.0\% to \(-3.76\%\), average \(-1.8\%\)). The researchers concluded that the effect of roadway grade on emissions per mile was too large to be ignored in emission models. However on a fuel specific basis (gram of
pollutant per gallon of fuel combusted), they found that emissions were almost independent of grade. This, of course, would suggest that the increased emissions observed when moving upgrade may have resulted from higher power demand and increased fuel consumption to overcome the grade load.

2.8.3.2 Roadway Gradient Studies
Kelly and Groblicki (1993) investigated the effects of grade, among other factors, on the emissions of one production vehicle (a GM Bonneville). They found that during moderate to heavy loads on the engine the vehicle ran under enrichment conditions which increased the emissions of CO by 2500% and HC by 40% with no significant NO increase, when compared to normal stoichiometric emissions rate. Compared to cold start emissions, emission levels on positive grades was 10 times more for CO and equal to cold start levels for HC.

Cicero-Fernandez et al. (1997a, 1997b) have published the results of a study performed specifically to quantify the effect of grade on emissions rate. Using a 1991 GM Chevrolet Lumina instrumented with an on-board data acquisition system, the road grade and emissions of the vehicle were sampled simultaneously; the road grade ranged from 0.0% to 7.0%. The results showed that for every 1.0% increment in road grade, there was an increase in emission of 0.04 g/mile for HC and 3.0 g/mile for CO. With the vehicle fully occupied (four passengers) on a 4.5% grade, the emissions increased by 0.07 g/mile for HC and 10.2 g/mile for CO.
Again it can be concluded from the results of these studies that the impact of grade is an enrichment effect on air-fuel ratio (a consequence of power demand), hence no significant increase in NO\textsubscript{x} was observed.

2.9 **Vehicle Dynamics: Theoretical Basis of Grade Effect on Engine Load**

Two opposing forces act on a vehicle to determine its straight line motion: tractive force and resistance forces. The tractive force is the engine force available to perform work at the interface of tires and road surface to move the vehicle. Resistance forces are the forces impeding vehicle motion and comprise three primary components: aerodynamic resistance, rolling resistance, and grade or gravitational resistance (Mannerling and Kilareski, 1990). This is illustrated in Figure 2-15.

Representing the rear and front tractive forces as \( F \) and the resistances as \( R \), and summing the forces along the vehicle’s longitudinal axis in Figure 2-15 gives the basic equation of vehicle motion:

\[
F = m \alpha + R_a + R_r + R_g
\]  

2.3
Figure 2-15: Forces Acting on a Road Vehicle (Mannering and Kilareski, 1990)

\[ R_a \] = aerodynamic resistance
\[ R_{rf} \] = rolling resistance of front tires
\[ R_{rr} \] = rolling resistance of rear tires
\[ F_f \] = tractive effort at front tires
\[ F_r \] = tractive effort at rear tires
\[ W \] = vehicle total weight
\[ \theta_g \] = angle of grade
\[ m \] = vehicle mass
\[ a \] = rate of acceleration
The difference between the tractive and resistance forces gives the vehicle acceleration:

\[ m \frac{da}{dt} = F - R_a - R_r - R_g \]  \hspace{1cm} 2.4

Aerodynamic resistance results primarily from the turbulent flow of air around the vehicle body in motion. The turbulence is a function of the shape of the vehicle, particularly the frontal area and the rear portion and is given as:

\[ R_a = \frac{1}{2} \rho C_D A_f V^2 \]  \hspace{1cm} 2.5

where \( \rho \) is the air density, \( C_D \) is the coefficient of drag, \( A_f \) is the projected frontal area of the vehicle in the direction of travel, and \( V \) is the vehicle speed. Equation 2.5 gives the aerodynamic drag as a quadratic function of the velocity. The basic assumption is that at low speed air flow around the vehicle is essentially characterized by laminar patterns: at higher speed, however, the air flow pattern goes into the turbulent region creating much higher resistance to the vehicle motion.

Rolling resistance refers to the resistance generated between the roadway/tire interface and results primarily from the deformation of the tire as it passes over the roadway surface. Tire penetration into the road surface and corresponding surface compression, and frictional motion due to tire slippage are other sources of rolling resistance. The
rolling resistance is approximated as the product of a frictional term and the weight of the vehicle acting normal to the road surface:

\[ R_r = f_r W \cos \theta_k \] \hspace{1cm} 2.6

where \( f_r \) is the coefficient of rolling resistance and is a property of the road surface and vehicle speed.

The grade resistance is the resistance to vehicle motion by the force of gravity. This depends on the vehicle weight and the severity of the grade, and can be either positive or negative depending on if motion is uphill or downhill, respectively. The grade resistance is given as:

\[ R_g = W \sin \theta_k \] \hspace{1cm} 2.7

Road grades are typically small so that \( \sin \theta_k = \tan \theta_k \); thus for a working approximation:

\[ R_g = m g \tan \theta_k = 0.01 m g \rho \] \hspace{1cm} 2.8

where \( \rho = (\text{rise/fall}) \times 100\% = \tan \theta_k \times 100\% \)

is the typical manner of expressing road grade as a percentage.
The needed climbing power \( P_g \) is calculated as:

\[
P_g = R_g V
\]

It has been shown (Bosch, 1996) that to climb a positive 18\% grade, a vehicle weighing 1500 kg and traveling at 40 km/h will require approximately 28.5 kW of climbing power to maintain the same speed on the grade. Thus the substantive effect of the grade is that this much extra power is demanded from the vehicle engine; as stated in previous sections, this has an enrichment effect in the fuel charge and a concomitant increase in the vehicle emissions.

2.10 **Methods for Collecting Roadway Geometric Data**

Numerous methods exist that can be employed to determine roadway geometric characteristics such as the grade and superelevation. Depending on the purpose, location, and available resources, these methods span from conventional land surveying techniques to advanced technologies such as photogrammetry and digital terrain models. Several factors are important in selecting any one method, and these include cost, time, workcrew safety, and the desired accuracy.
2.10.1 Conventional Surveying

The most common conventional surveying method for determining roadway geometric characteristics is the leveling survey. This method relies on the determination of relative elevations between points along the road to determine the longitudinal and lateral slopes; these are translated into roadway grade and banking, respectively. Relative elevations with leveling survey are typically accurate to a hundredth of a foot (Moffit and Bossler, 1998). Roadway alignments are also determined with these methods by traversing road sections using angles and distances. Modern total stations can measure spot elevations, angles, and distances simultaneously from one location. This enables the accurate computation of point coordinates that can be used to determine both horizontal and vertical alignment of roadway.

The major problems with conventional survey methods are safety and the time required to complete a survey. Since surveyors need to be physically present on the road, the use of this method sometimes involves some restricted traffic operation; on high speed roads such as freeways this is either unsafe or impractical.

2.10.2 Survey Instrumented Vehicles

This method employs vehicles equipped with survey instruments to determine roadway geometric characteristics. One such instrument is the Vangarde 505 system, which is one of the leading technologies in this area. The Vangarde 505 uses an infrared electronic distance measurer (EDM) and a theodolite that allows measurements to targets on the
road surface from a static, remote location. The combination allows for the simultaneous measurement of distances and horizontal and vertical angles on a segment-by-segment basis. In operation, the vehicle is parked on a road shoulder or median; the operator shoots the EDM at target locations along the road, and the distance and angles are recorded on a data logger. Then the vehicle is moved to the next segment and the process repeated. The data is subsequently converted to road grade and banking. This system provides data to an accuracy of two millimeters.

Compared to conventional survey, the operation of the Vangarde is safer and does not impact traffic operation. Though most of the work is done from the vehicle, the system still requires conventional survey to establish controls. The system does not perform well on new asphalt and on wet pavement because of the light absorbing / scattering effect of these surfaces. It is also very costly and time intensive.

2.10.3 Remote Sensing

Remote sensing data are collected from high altitude satellites, such as the LANDSAT, or from high altitude aerial photography. These data are used for determining roadway geometry through photographic aerotriangulation, or through United States Geological Survey (USGS) Digital Elevation Models (DEM). The accuracy of the DEM data is adequate to support computer applications that analyze topographic features to a level of detail similar to manual interpretations of map scales not larger than 1:100,000. At larger scales the elevation data is much less reliable (USGS, 1996)
Since most existing EDM data have very low resolution, the grade data obtained from these methods are inaccurate. Moreover, most highways pass through extensive cut and fill sections that are usually not accounted for in satellite or photogrammetric images because of limited resolution. The accuracy of photogrammetric mapping is directly related to the flying height; the lower the flying height the more accurate the data. Accuracy of 3/100 of a foot have been achieved with a flying height of 60 ft above mean terrain (AMT). A major disadvantage of low altitude mapping is that it requires a lot of photographs and processing time. Thus, although the accuracy of this method may be enhanced with low altitude photography, the time and cost becomes prohibitive.

2.10.4 As-Built Plans

As-built plans are developed from design plans used for the construction of a roadway. They give information on the geometry of various segments of the road as it was built. However, the final construction details of a road may differ significantly from the original plans because of un-anticipated conditions in the field. Data extracted from as-built plans are very accurate especially if the plans were adjusted using field survey data to reflect the actual alignment after the road was constructed. The major disadvantage of this method is that as-built plans are not always available (some existing roads were constructed without any formal design or plans), and it can be labor and time intensive extracting data from them.
2.10.5 Global Positioning Systems (GPS)

Several efforts have been made to use either conventional or attitude GPS methods to determine roadway geometry (Awuah-Baffour, 1997; Quiroga, 1996; Barth et al., 1994). See Section 4.4 for a detailed discussion of GPS. In conventional GPS a single antenna connected to a roving receiver is used to determine the three dimensional coordinates of points along a road. Using post processing algorithms, the GPS data is corrected for errors using data from an established base station receiver. The relative difference in the Z-coordinates of two consecutive points, and the straight line distance between them is used to calculate the grade at the section of roadway between the two points.

Attitude is defined as the orientation of a vehicle (body-fixed frame) in a specific coordinate system with respect to a reference system. Three parameters are used to define attitude: the Euler angles for roll, pitch, and yaw. Attitude GPS utilizes a set of four antennas (or two, if all that is needed is longitudinal alignment) to simultaneously determine the roll, pitch, and attitude of a moving vehicle, based on the differences in their coordinates at a given time. The pitch corresponds to the up and down (vertical) changes in the movement of the vehicle on the road surface and is readily translated into the roadway grade. The roll is translated into banking or super-elevation, and the heading defines the directional orientation of the vehicle measured as an azimuth angle from the north.
Studies have shown that both conventional and attitude GPS have been successfully utilized in limited applications to determine road grade (Awuah-Baffour, 1997b, Quiroga 1996). However, both methods become problematic in expanded uses that include areas with urban canyons and tree canopies. Overhead obstructions in these areas interfere with and degrade the GPS signals. Ultimately the consistency of the data acquired through this method was shown to be unreliable.

This chapter presented both policy and technical background materials on vehicle emissions, vehicle emissions modeling, the effect of roadway grade on vehicle emissions, and some methods for collecting roadway grade data. The material highlighted some of the deficiencies in current emissions modeling procedures, focused on the need for grade data in emissions models, and ended by discussing shortcomings in available methods for collecting grade data. In the next chapter, the framework for this research, showing how the specific goal of developing a more efficient grade measurement methodology suitable for generating data for vehicle emissions modeling will be attained, is presented.
CHAPTER III

RESEARCH FRAMEWORK

3.1 Statement of Problem

Current EPA and CARB emissions models utilize fleet average emission rates determined from laboratory tests of vehicles operating under standard conditions. However because the standard conditions are not representative of real world conditions, several published research have called into question the reliability of outputs from emissions models. Also the expanded use of the emissions models for the assessment and design of congestion mitigation and emission control strategies calls for outputs at increasingly smaller scales. But because the models use highly aggregate data, the resulting outputs lack the spatial resolution and accuracy adequate for evaluation at such scales. Numerous important factors that affect vehicle emissions are not considered by current emissions models.

Of pivotal concern to this research is the fact that roadway geometric characteristics, particularly road grade, is not incorporated in the standard conditions used in the models nor factored into the correction factors. Several research publications have shown that the effect of grade can increase emissions by orders of magnitude over what is predicted by the emissions models (Pierson et al., 1996; Cicero-Fernandez et al., 1997b; ). This
happens because of the extra load induced by the grade on the engine, and has been identified as a major source of model misrepresentation.

In a report to the Chairman of the House Subcommittee on Oversight and Investigations, the US General Accounting Office had described the major limitations in EPA's MOBILE model and the process for improving future versions of the model (GAO, 1997). The omission of grade induced emissions in the standard FTP cycle was identified as one of the major limitations. However it was not expected that the next update version of the model (MOBILE6) would have adjustments for road grade. While expressing uncertainty about the amount of grade-related emissions, the major reason adduced for this was the non-availability of a cost-effective method to map grade on the millions of miles of roadways in the country. This would be required of state and local agencies if adjustment for road grade is made in the model.

Since emission models are used by air quality management agencies both for inventory and conformity evaluation, it is important that model input and assumptions reflect as closely as possible the true conditions. In particular, the EPA and the states rely on the models to estimate future emissions and assess emission control strategies for approval. Consequently, to the extent that the models erroneously estimate emissions, approval could be given for control measures that may not be sufficient to attain air quality standards, resulting in long term negative health and cost impacts; conversely, states could be required to implement additional control measures (often with huge cost
implications) that may be entirely unnecessary. Clearly, whether under- or over-predicting emissions, the implications of erroneous model output are considerable. But the model, as is said, can only be as good as the data from which it was developed, hence the importance of adequately representative data both in the development and utilization of the models is crucial. This research seeks to develop a means of meeting one of the data needs of emerging emission models – roadway grade data.

3.2 Research Hypothesis:

In Chapter 2 we presented different methods used to acquire roadway geometric data. All of these methods, however, suffer from some shortcomings that make them unsuitable for grade data collection in the form, scale, and accuracy needed for the data to be useful for incorporation into the emerging GIS-based emission models. The basic requirement of unique coordinates to identify the position of a given grade value cannot be readily achieved with any of those methods.

This research is based on the hypothesis that an integrated system comprising a fiber optic gyroscope and a GPS receiver can be used to simultaneously determine both the grade and the coordinates of points on a roadway. It is hypothesized that the gyroscope output can be statistically calibrated and modeled to give a consistent and repeatable measurement of roadway grade. The gyroscope output will be integrated with a GPS output that establishes the unique coordinates of each grade output at the needed spatial
resolution. The spatially referenced data is thus in a format where it can be readily incorporated into a GIS for use in vehicle emissions modeling.

3.3 Research Goal

The major goal of this research is to develop an efficient methodology to reliably measure roadway grade in kinematic mode at such spatial resolution that the data can be usefully employed for policy and project evaluation at different scales. The final result will establish a GIS-based database of linear sequence of points along a given road link, identified by unique x- and y- coordinates (longitude and latitude), and the associated grade value. With this data, the effect of road grade on vehicle exhaust emissions can be correctly ascertained and subsequently incorporated into the emerging GIS-based modal model of vehicle emissions. The ultimate impact of this research will lead to the eventual development of adjustment factors for the effect of grade in emissions models. In order to accomplish this overall goal the following objectives have been identified as necessary sub-tasks:

Objective 1: Develop a system that has the capability of recording roadway grade data in kinematic mode, and the output is compatible for incorporation into a GIS. The system comprises of three components: a fiber optic gyroscope that is capable of measuring the road grade and giving the output in digital format, a GPS receiver that tags each
gyroscope output with its unique latitude and longitude coordinates, and a field durable computer with dual serial ports for data logging.

Objective 2: The second objective is to collect data to test and calibrate the system output based on established statistical principles. Several test data would be collected to determine the accuracy and consistency of the system to give reliable and repeatable data. Test runs would be made on several road segments with different grade severity to study the range of grades over which the equipment can be reliably used. Factors that could affect the performance of the system would be incorporated in the tests to establish appropriate use conditions.

Objective 3: Based on the calibration exercise, formulate a robust calibration model that can be applied to the system output in a consistent and repeatable manner. The calibration model will be used with subsequent data collected with the equipment and the vehicle to predict roadway grade. Consistency here means that the same results can be obtained by different operators of the system under similar conditions; and repeatability requires that multiple results from the same road measurements be comparable. Thus the model developed from the test exercise would be applicable to the prescribed use conditions and be capable of giving reliable measurement of road grade.

Objective 4: Validate the system methodology with a roadway network. With the previous three objectives successfully accomplished, the grade data on a road network
would be mapped based on the developed methodology. The grade data would then be available for incorporation into emission models and help to advance the accuracy of the model output.

3.4 Research Scope

The scope of this research is to develop and test a methodology for mapping road grade in a form that the data could be used in the emerging GIS-based vehicle emission models. The road grade data obtained by this method is spatially resolved so that it can be readily incorporated in a GIS environment. Several research efforts have documented the effect of grade severity on vehicle emissions characteristics. However, there is not a lot available in the literature about the actual quantitative relationship between grade severity and emissions rate or production. The appropriate method to incorporate grade data into vehicle emission models will depend both on this relationship and on the form in which the grade data is available.

The grade data obtained through the methodology developed in this research has a utility that enables the user to change the spatial resolution; in other words, the spatial resolution can be customized to fit the user’s needs. The grade data can therefore be incorporated into the model either as a continuous quantity (instantaneous, second-by-second grade value) or as a discrete quantity (segmented into appropriate grade classes that may be defined as "flat", "rolling", or "hilly") to represent increasing grade severity. An
investigation of which of these approaches will actually be used to incorporate the grade data into existing vehicle emissions models is beyond the scope of this research. This is because the developers of the models have not yet made such a determination. However, actual utilization of the grade data in the GIS-based MEASURE modal emissions model is recommended for future studies.

3.5 Significance of Work

This dissertation presents the results of a study aimed at developing a methodology to collect roadway grade data. The contribution of this research to current vehicle emissions modeling practices and to other programs is significant.

Primarily, the availability of road grade data will enable the establishment of the significance of the link between road grade and vehicle emissions production; the threshold value where the road grade becomes an important emissions factor can thus be determined. The ultimate impact will be the development of adjustment factors for the effect of road grade in emissions models, and a better representation of real world conditions in these models. Secondly, it provides a method for agencies to adopt in collecting roadway geometric characteristics data for inventory and other purposes.
CHAPTER IV

RESEARCH PROCEDURE

This chapter provides detailed description of the procedures for accomplishing the research objectives identified in Chapter III. A flow chart detailing the interconnections of the procedures is shown as Figure 4-1. The flow chart comprises five major sections. The first section identifies the hardware system components, while the second part shows the data analysis process and the development of a calibration model for the gyroscope output. The third section shows the process automation for implementing the methodology, and the fourth corresponds the development of the GIS-based grade database. The fifth is not an integral part of this research, but it identifies a major project in which the grade data will be utilized, namely, utilizing the grade data in the Georgia Tech MEASURE model.

The first objective is to select appropriate hardware system components that can digitally record and store road grade data and the associated spatial coordinates. Two preceding studies at Georgia Tech provided input into this process, as explained in Section 4.1. The conclusions from these studies were important in the selection of appropriate system components within our resources. Because we operate under constrained resources, the overriding objective is to develop a system that will efficiently accomplish the research
Figure 4-1: Flow Chart of the Research Procedure

1. SYSTEM COMPONENTS
   - DMU-FOG
     Dynamic Measurement Unit Optical Gyroscope
   - GEORESEARCH WORKHORSE
     GPS Receiver
   - DATABRICK
     Portable Data-logging Computer

II. STATISTICAL ANALYSIS AND DEVELOPMENT OF CALIBRATION DATA
   - HAND TRUCK DATA
   - VEHICLE (JEEP) DATA
   - DATA ANALYSIS AND CALIBRATION
   - DATA VALIDATION
   - DMU-FOG DATA EVALUATION WITH X-VIEW SOFTWARE

III. PROCESS AUTOMATION AND APPLICATION
   - PROCESS AUTOMATION FOR THE ANALYSIS OF THE INTEGRATED DATA
   - FINAL ROADWAY GRADE AND POSITION DATA
   - CONVERSION OF DATA INTO GIS (TRANSCAD) FORMAT
   - GIS-BASED ROADGRADE DATABASE
   - UTILIZATION OF ROADGRADE DATA IN MEASURE MODEL
   - MATCH GPS_GYRO.PL
   - CLEAN_GYRO.PL

IV. DATABASE DEVELOPMENT
   - GISEX PROGRAM
   - POST PROCESS GPS DATA WITH POSTPOINT SOFTWARE

V. DATA UTILIZATION
   - CLEAN_GPS.PL
   - DMU EXAMPLE VI
   - WH POSITION STATUS VI

HARDWARE SYSTEM COMPONENT DESIGN
goal. The efficiency goal is based on the capability of state and local transportation and air quality management agencies to afford the resources to develop a similar setup. To incorporate grade correction factors into vehicle emission modeling, these agencies would eventually be required to map the road grades in their jurisdictions. The next three objectives involve data collection, data analysis, and data interpretation. Subsequent sections in this chapter present theories and principles of the workings of the system components, and explain procedures for data collection. Examples of the data outputs are also shown; however a discussion of the data analysis and interpretation is deferred to Chapter 5 for full treatment.

4.1 Hardware System Design

In addition to time and cost efficiency, the hardware system selection is also influenced largely by the purpose for which the final data would be used. In this case, a grade database will be developed from this research for use in the emerging GIS-based emission models in spatially allocating vehicle emissions that are a function of the road grade. It is therefore crucial that the system be capable of simultaneously recording the grade data and the spatial information for relating the measured grade to a position. In the selection of the system hardware, this study benefited from the results of two previous studies.
Awuah-Baffour (1997) investigated the use of GPS for kinematic determination of roadway grade. In this pivotal study, two configurations employing Ashtech ADU and then Ashtec Z12 receivers were undertaken to determine the feasibility of utilizing the three dimensional position outputs of GPS data to simultaneously determine position, roadway grade, and roadway superelevation.

In the configuration that used Ashtec ADU receivers, a four-antenna array was mounted on a vehicle in a T pattern as shown in Figure 4-2. This configuration was expected to simultaneously provide the vehicle pitch and roll which were interpreted as effectively the roadway grade and superelevation (or banking), respectively. The hypothesis behind this proposal is as follows: the difference in the relative elevations of the front and rear of the vehicle is determined from the z readings of antenna 1 and antenna 2 at the same epoch, while that of antenna 3 and antenna 4 determines the difference in the relative elevations of the right and left sides of the vehicle. The roadway grade (or pitch) is then calculated by dividing the relative elevation difference between the front and rear by the distance between antenna 1 and antenna 2. Similarly, the roadway superelevation (or roll) is calculated between antenna 3 and antenna 4.

In the second configuration using Ashtech Z12 receiver, a single GPS antenna was mounted on the vehicle. The theoretical premise of this approach is fairly straightforward. Consider the three dimensional coordinates of two points that are relatively close together: with the x- and y-coordinates the distance between the points
Fig 4-2: Four GPS Antenna Configuration for Determining Vehicle Pitch and Roll (Awuah-Bafour, 1997)
is determined from Pythagorean principles. The difference in the relative elevation of the two points is determined from their z-coordinates. The average grade between the two points is then calculated by dividing the difference in relative elevation by the distance between the two points. In a vehicle moving at 45 mph and collecting GPS data at one second interval, the straight line horizontal distance between two consecutive points is about 66 ft. On freeways and major arterial roads where design standards for vertical and horizontal curve radii are stringent, it is reasonable to posit that the road grade in that distance will not change significantly, even at crests and valleys. Thus, the average grade between consecutive points can be interpreted as a point grade and assigned either to the beginning or to the end point.

While the theoretical underpinnings seemed well founded, the practical issues in both approaches will prevent widespread implementation of the procedures. The results of this study showed that several factors, not easily controlled by the operator, affect the proper utilization of GPS data for this purpose. These factors essentially manifest as GPS signal loss or signal degradation as a result of obstruction or interference from such myriad sources as overhead bridges, tree foliage, buildings, high-tension electricity cables, etc. The deleterious effects of signal degradation is particularly severe with z readings (altitude measurement) from which the grade is largely determined. Under these conditions, the single Z12 receiver configuration was found to perform better than the four antenna array ADU configuration. This is because the ADU configuration requires all four receivers to be functional, and a signal loss by one affects the entire system.
Because both methods depend largely on uninterrupted GPS signal reception, signal loss, as is commonly experienced on roadways, is also a major drawback in implementing the procedures.

Signal loss results from loss of satellite lock by the receiver, and this usually occurs at areas with overhead obstruction or interference, the effect being that no data is recorded in the interim. After the vehicle comes into the clear, the receiver takes some time (typically between 2 seconds to as much as 5 minutes) to search and re-establish satellite lock and start proper signal reception. It is significant that the operator has little control over this process, and loss of satellite lock can also occur even in open skies with strong electromagnetic interference, unknown to the operator. The resulting data appears intermittent and non-continuous.

To overcome this, multiple runs on road segments are undertaken to collect data to fill in where there have been signal loss the previous runs. An alternative approach involves stopping the vehicle until satellite lock is re-established before continuing. In either case the efficiency of quickly and accurately determining the road grade is sacrificed. The field implementation of both configurations beyond the well controlled environments of test routes proved to be labor intensive in numerous subsequent trials, hence the procedure was not pursued further.
In the second study, Wolf et al. (1999) investigated the spatial accuracy of different GPS receivers with regard to route choice data collection; five receivers from four different manufacturers were tested. A vehicle with all five receivers was driven through a predefined route designed to represent a variety of commuter route characteristics in the Atlanta metro region. The route included the following road segments: urban arterials and freeways with open sky views and with overpasses, arterials and freeways with heavy, intermittent tree canopies, and arterials through the downtown area with high-rise buildings (urban canyons). The spatial data from each receiver were brought into a GIS and matched against a base map of street network incorporating the route. The base map was a geometrically corrected version of the US Census Bureau’s TIGER files.

The percentage of the data that falls within predefined buffers created around the centerline of the street network was used as a measure of the accuracy of each receiver. The results, reproduced in Table 4-1, showed that the GeoResearch Workhorse receiver gave superior results to the other receivers tested with 63% of the data falling within 10 meters of the representative road centerline, and 85% falling within 30 meters. This study investigated the accuracy of only the x- and y- coordinates (Longitude, Latitude) and does not include the z readings (altitude).

Based on the results of these two studies, fulfilling the goal of this research will depend upon successfully integrating a grade measurement and acquisition system with a reliable GPS receiver. The grade measurement component will output the grade data while the
<table>
<thead>
<tr>
<th>GPS</th>
<th>&lt; 5 meters</th>
<th>&lt; 10 meters</th>
<th>&lt; 30 meters</th>
<th>&lt; 50 meters</th>
<th>&lt; 100 meters</th>
<th>&lt; 500 meters</th>
</tr>
</thead>
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<td>Garmin 35LP</td>
<td>15%</td>
<td>31%</td>
<td>83%</td>
<td>96%</td>
<td>99%</td>
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<td>89%</td>
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<tr>
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<td>33%</td>
<td>63%</td>
<td>85%</td>
<td>90%</td>
<td>94%</td>
<td>96%</td>
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<tr>
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<td>60%</td>
<td>74%</td>
<td>88%</td>
<td>99%</td>
</tr>
<tr>
<td>3S GNSS-300</td>
<td>10%</td>
<td>19%</td>
<td>46%</td>
<td>63%</td>
<td>78%</td>
<td>88%</td>
</tr>
</tbody>
</table>

¹Test data excluded urban canyon segments along the route
GPS receiver will output the spatial coordinate (x, y) data. By integrating both data, the location of each grade output will be determined. The selected system setup comprises three primary components:

- a fiber optic gyroscope (as the grade measurement/acquisition component),
- a GPS receiver (as the spatial data acquisition component), and
- a data logging computer with dual serial ports and data acquisition software for interfacing between the GPS receiver and gyroscope (for data visualization and storage).

The selected gyroscope is the Dynamic Measurement Unit – Fiber Optic Gyroscope (DMU-FOG) manufactured by Cross Bow Technology, Incorporated; the GPS receiver is the Workhorse receiver manufactured by GeoResearch, Incorporated, and the data logging computer is the Databrick manufactured by the Datalux Corporation. The test vehicle is a 1995 manual transmission Jeep Cherokee.

The suitability of the NAVSTAR GPS for kinematic spatial data acquisition had been demonstrated by other studies (Awuah-Baffour, 1997; Quiroga, 1997); thus, we only had to determine the most suitable GPS receiver within our resources to employ. The study by Wolf et al (1998) established the GeoResearch Workhorse as the most appropriate for our use. On the other hand, the grade measurement component (the DMU-FOG) had not been studied, and would have to be evaluated and calibrated as part of this study. This activity forms a major part of this research effort. But, before putting the hardware
components to use, a discussion of the theory and principles of gyroscopic motion and
the global positioning system is in order.

4.2 Principle of Gyroscopic Motion

Gyroscopic motion occurs whenever the axis about which a rigid body is spinning is
itself rotating about another axis. The two fundamental characteristics of a gyroscope are
gyroscopic inertia and precession, which are based on Newton’s third law of motion and
the principle of conservation of momentum, respectively. A complete description can be
found in texts on engineering dynamics such as Sandor, 1987, and Kleppner and
Kolenkow, 1998. The most common manifestation of gyroscopic motion is observed
when a freely spinning disc is torqued about an axis normal to the spin axis, and it turns
(precesses) about a third axis that forms an orthogonal triad with the spin and torque
vectors (see Figure 4-3). Thus we identify the spin axis (\(\mathbf{p}\)), the torque axis (\(\mathbf{M}\)), and the
precession axis (\(\mathbf{\Omega}\)), where the familiar right-hand rule identifies the sense of rotation of
the vectors. The direction of the precession is such that it turns the spin vector towards
the torque vector.

With suitable mounting in gimbal rings (Figure 4-4), the gyroscope can be isolated from
external moments and its axis retains a fixed direction in space regardless of the
movement of the base structure to which it is attached. Thus, the angle between the spin
axis and the plane of the base is a measure of the angular displacement of the base from
Figure 4-3: Gyroscopic Precession Exhibited by a Spinning Disc
(Meriam and Kraige, 1998)
Figure 4-4: Isolation of a Spinning Disc in Gimbal Rings (Meriam and Kraige, 1998)
the fixed datum provided by the spin axis. Depending on the set-up, a gyroscope can serve as an angular rate sensor or as a directional compass. Used with mechanical accelerometers, precise measurements may be performed, and this is the basis of inertial guidance and navigation systems. The mathematical integration of acceleration and rotation rates yields the attitude and the trajectory of a vehicle.

However, gyroscopes based on mechanical principles and having moving parts as described above are susceptible to shocks and vibrations, and are poorly suited for use in dynamic environments. The effect of shock and vibration introduce noise in the gyroscope output; in addition if the magnitude of the vibration exceeds the range of the instrument, the output can saturate. These introduce errors in the gyroscope output. In 1913, Sagnac demonstrated that it is possible to detect rotation in inertial space with an optical system that has no moving parts. In addition to other benefits, this approach offers much improvement for applications in dynamic conditions. The complete treatment of this topic can be found in specialized texts; but for the ready understanding of how such a gyroscope can be employed to determine roadway grade, a simplified description based on optical mechanics is provided here.
4.3 Principle of the Fiber-Optic Gyroscope

The fiber-optic gyroscope is based on the Sagnac effect, which produces a phase difference $\Delta \Phi_k$ between two counter-propagating waves proportional to the rotation rate $\Omega$ in a ring interferometer (Lefevre, 1993). In Sagnac’s original experimental set-up, a beam splitting plate separates an input beam into two waves which propagate in opposite directions along a closed polygonal path defined by mirrors. If the whole system is rotated, a lateral shift of interference fringes of the two beams is observed.

This phenomenon is explained with the illustration in Figure 4-5. Consider a regular polygonal path $M_0M_1 \ldots M_{N-1}M_0$; at rest the opposite paths are equal, but in rotation around the center, the co-rotating path is increased to $M_0M'_1 \ldots M'_{N-1}M'_N$ and the counter-rotating path is decreased to $M_0M''_1 \ldots M''_{N-1}M''_N$. In the inertial frame of reference the points $M_i$ move on a circle of radius $R$, and light propagates along polygon sides $M'_iM'_{i+1}$ or $M''_iM''_{i+1}$ instead of $M_iM_{i+1}$. In Figure 4-6 the first side of the co-rotating polygonal path becomes $M_0M'_1$. Let $2\theta$ be the angle $M_0OM_1$, $\delta \theta$ the angle $M_1OM'_1$, $L_M$ the length $M_0M_1$, and $\delta L_M$ the path length increase $M_0M'_1 - M_0M_1$. Then:

$$\delta L_M = M_1M'_1 \cos \theta$$  \hspace{1cm} (4.1)

and $M_1M'_1 = R \delta \theta$  \hspace{1cm} (4.2)
Figure 4-5: Path Change in a Ring Interferometer with a Regular Polygonal Path:
(a) At Rest
(b) Co-Rotating Path
(c) Counter-Rotating Path
(Lefevre, 1993).
Figure 4-6: Geometric Analysis of the Sagnac Effect on one Side of a Polygonal Path (Lefevre, 1993).
The angle $\delta \theta$ is the angle of rotation in the time the beam propagates between $M_0$ and $M_1$. Therefore:

$$\delta \theta = \frac{L}{c} \cdot \Omega$$

where $c$ is the light propagation velocity.

By geometry, $L = 2R \sin \theta$, and the area of the triangle $M_0OM_1$ is $A_t = (R \sin \theta)(R \cos \theta)$. Therefore:

$$\delta L = 2 \frac{A_t \Omega}{c}$$

The path increase $\delta L$ corresponds to an increase $\delta t^*$ of the propagation time:

$$\delta t^* = \frac{\delta L}{c} = 2 \frac{A_t \Omega}{c^2}$$

The same increase is repeated for each side of the polygon, and the opposite variation $\delta t^* = -\delta t^*$ in the counter-rotating direction. The difference $\Delta t_v$ of propagation time between the two opposite closed paths is then:

$$\Delta t_v = 2 \left( 2 \frac{\Sigma A_t \Omega}{c^2} \right) = 4A_\Omega / c^2$$

where $\Sigma A_t$ is the sum of all the triangular areas (i.e. the entire enclosed area $A$). Measured in an interferometer, this time difference yields the phase difference:

$$\Delta \phi_R = \omega \cdot \Delta t_v = 4\omega A \Omega / c^2$$

where $\omega$ is the angular frequency of the wave.
This result is very general and can be extended to any axis of rotation and to any closed path, even if they are not contained in a plane, using the scalar product \( A \cdot \Omega \).

\[
\Delta \phi_R = \left( \frac{4\omega}{c^3} \right) A \cdot \Omega
\]

where \( \Omega \) is the rotation rate vector and \( A \) is the equivalent area vector of the closed path defined in terms of the line integral:

\[
A = \frac{1}{2} \oint r \times dr
\]

where \( r \) is the radial coordinate vector.

This presentation can be extended to a circular path, which would be the limit of a polygonal path with an infinite number of sides. The same effect is also observed in a fiber coil. Because the Sagnac effect is proportional to the rotation rate vector \( \Omega \), it can be enhanced for adequate sensitivity with a multi-turn path of fiber coil. The Sagnac phase difference then becomes:

\[
\Delta \phi_R = \left( \frac{2\pi LD}{\lambda c} \right) \Omega
\]

where \( L \) = length of fiber in coil

\( D \) = effective coil diameter

\( \lambda \) = mean optical wavelength

\( c \) = velocity of light in vacuum

\( \Omega \) = angular velocity about sensitive axis
Figure 4-7 illustrates the practical configuration of the fiber optic gyroscope similar to the one used in this study. It consists of a fiber coil, two directional couplers, a polarizer, solid state optical source (laser), and detector. A piezoelectric (PZT) disc applies a non-reciprocal phase modulation. Light from the laser traverses the first directional coupler, polarizer, and second directional coupler where it is split into two signals of equal intensity that travel around the coil in opposite directions. At the directional coupler the two waves, having traversed the coil in opposite directions, are combined in an optical interferometer, returning through the polarizer where half of the light is directed by the first coupler into a photodetector.

The light intensity returning from the coil to the polarizer is a raised cosine function of the Sagnac phase shift, having a maximum value when there is no rotation, and a minimum value when the optical difference is ±π (half a wave-length). A dynamic phase bias is applied to discriminate between the sense of rotation: clockwise rotation is typically taken as positive and anti-clockwise rotation is negative. The photo-detector output is converted to voltage and calibrated to give a digital read-out of the rotation angle. If the gyroscope is rigidly mounted in a vehicle parallel to the horizontal plane, the rotation angle will then correspond to the deviation of the roadway plane from its previous position. By initializing (zeroing) the gyroscope on a level plane (0% grade), subsequent readings effectively correspond to the integrated roadway grade from the previous reading.
Figure 4-7: Block Diagram of the Optical and Electronic Circuits of an Open Loop Fiber-Optic Gyroscope (Bennett et. al., 1998)
4.4 Overview of the Global Positioning System (GPS)

The concept of satellite navigation was conceived following the launch of the Russian-built Sputnik I in 1957. Scientists developed a method of tracking the satellite's orbit by observing the Doppler shift of the radio signal broadcast from the satellite. By reversing this process, it was proposed that a navigator's position could be determined by tracking the Doppler frequency of a radio signal broadcast by a satellite that had a precisely known orbit. The U.S. Navy took advantage of this new technology to provide accurate position updates with inertial navigation equipment on ships and submarines around the globe with the TRANSIT satellite navigation system, which became operational on U.S. Polaris submarines in 1964.

With the development of precision atomic clocks in the 1960s, it became possible to design a satellite constellation which carried a network of clocks precisely synchronized to a common time reference. By broadcasting time-coded signals, a receiver could measure the distance (or range) to a satellite by observing the transit time of the radio signal from the satellite. The first satellite to implement this passive ranging technique was the TIMATION I satellite launched by the U.S. Navy in 1967.

The U.S. Air Force (USAF) initiated a program in 1964 to develop and test a coded transmission technique that would provide precise ranging and timing data using a signal modulated with a pseudo-random noise (PRN) code. This has the effect of spreading the signal spectrum over the bandwidth of the modulation code. When the satellite signal is
regenerated by correlating with the modulation code at the receiver, any other interfering signals are spread and weakened relative to the desired satellite signal. This feature also allows all of the satellites in the constellation to broadcast on the same frequency without interfering with each other. This feature is known as code division multiple access (CDMA). In 1973, the USAF and US Navy programs were combined into the Navigation Technology Program, which later evolved into the NAVSTAR GPS program.

4.5 Description of NAVSTAR GPS

The NAVSTAR GPS program\(^1\) was developed primarily as a military navigation system. As such, it was designed to offer two classes of navigation services: a Precision Positioning Service (PPS) restricted to government and other authorized users; and a Standard Positioning Service (SPS) that is open for ordinary and commercial use. The GPS infrastructure consists of three major segments: the space segment, the control segment, and the user segment.

4.5.1 Space Segment

The space segment consists of the satellites (known in GPS lingo as space vehicles, SV) which transmit radio signals from space. The operational constellation consists of 24 earth-orbiting satellites (21 navigational satellites and 3 active spare units) arranged in six orbital planes. The nominal circular orbit is 20,200 kilometers (10,900 nautical miles).
altitude inclined at an angle of 55 degrees to the equatorial plane. There are four satellites in each orbit, equally spaced at 60 degrees apart. The orbits repeat the same ground track (as the earth turns beneath them) once each day, thus, they are 12-hour orbits. This constellation provides the user with between five and eight, (but at least four) satellites visible from any point on the earth. Each satellite transmits two L-band radio frequency signals - the Link 1 or L1 frequency at 1575.42 MHz, and the Link 2 or L2 frequency at 1227.60 MHz. The signals are broadcast using spread spectrum techniques employing two different spreading functions - a 1.023 MHz coarse / acquisition (C/A) code or Standard Positioning Service (SPS) on L1 only, and a 10.23 MHz precision (P) code or Precise Positioning Service (PPS) on both L1 and L2. Superimposed on the C/A codes are low-rate navigation message data, consisting of status information, satellite ephemerides, satellite clock bias, and Coordinated Universal Time (UTC) synchronization information. The C/A code has been purposely omitted from the L2 channel, thus allowing the US Department of Defense (DoD) to encrypt the P code and change it to a Y code. The encrypted Y code requires a classified module for each receiver channel and is for use only by DoD authorized users with cryptographic keys. With this ability (commonly termed selective availability) the US Department of Defense is able to degrade the quality of position data received by non-military users.

1 The Russian Government operates a second GPS program called GLONASS. It was believed that both systems could eventually complement each other, but little in this regard has developed thus far. The GLONASS system does not employ selective availability.
4.5.2 The Control Segment

The control segment consists of a system of five tracking stations located around the world, with the Master Control Station (MCS) located at Falcon Air Force Base in Colorado. The other monitor stations are located at Hawaii, Kwajalein, Diego Garcia, and Ascension Island. These monitor stations passively measure signals from the satellites which are incorporated into orbital models for each satellite. The models compute precise orbital data (ephemeris) and clock corrections for each satellite. The master control station periodically uploads the ephemeris and clock data to the satellites. The satellites then incorporate subsets of the orbital ephemeris data with the radio signals they send to GPS receivers. Thus, all the satellites are monitored for accuracy on a continuous basis. In the event that one of the navigational satellites malfunctions, the master control station activates one of the active spare satellites to replace it.

4.5.3 The User Segment

The user segment consists of an assembly of GPS receivers and antenna configurations for purposes that include military, research, and various civilian applications. The fundamental observable in GPS positioning is the spatial distance between the observed satellite and the receiver. GPS receivers convert the satellite signals into position, velocity, and time estimates. Due to inherent errors in GPS positioning (see Section 4.7 for a description of GPS error sources), the distances computed are termed pseudoranges. These are computed using the time of travel of the signals from the satellite to the receiver and the signal velocity. GPS signals are electromagnetic waves with speeds
equal to the speed of light \((c = 299792458 \text{ms}^{-1})\). Because the receiver clock and the satellite clock cannot be synchronized exactly, there is always an error in the computed time of travel of the signals, hence an error in the computed distances. Thus, to determine the three dimensional coordinates of a point, four satellites need to be observed to generate the four dimensions of \(X, Y, Z\) (position) and \(T\) (time).

### 4.6 Technical Concept of the GPS

Suppose the coordinates of a point on earth \(P\) (\(X, Y, Z\)) are to be determined (see Figure 4-8). A GPS receiver placed at point \(P\) receives signals from satellites \(S_1, S_2, S_3, \text{and } S_4\). The distance between receiver and satellite at measurement epoch \(t\) is defined as:

\[
R_i^s(t) = D_i^s(t) + c\Delta\delta_i^s(t)
\]

where \(R_i^s(t)\) is the measured carrier pseudorange between satellite \(s\) and observing position \(i\), \(D_i^s(t)\) is the geometric distance between the receiver and the satellite, \(c\) is the speed of light, and \(\Delta\delta_i^s(t)\) is the combined satellite and receiver clock offset. This clock offset is defined as:

\[
\Delta\delta_i^s(t) = \delta^s(t) - \delta_i(t)
\]

where \(\delta^s(t)\) is the satellite clock error which is part of the ephemeris information broadcast to the ground receiver and is therefore known, and \(\delta_i(t)\) is the receiver clock error, which is unknown.
Figure 4-8: GPS Concept: Pseudo-range Determination to a Point on Earth
Using the three dimensional Cartesian coordinates of the satellite’s and the receiver’s positions, the geometric distance between the two is determined as:

\[ D_s(t) = [(X_s(t) - X_i)^2 + (Y_s(t) - Y_i)^2 + (Z_s(t) - Z_i)^2]^{1/2} \]  

4.13

where the vectors \( X_s(t), Y_s(t), Z_s(t) \) are the geocentric coordinates of the satellite’s position at epoch \( t \) and \( X_i, Y_i, Z_i \) are the coordinates of the receiver.

Now, representing propagation errors due to atmospheric and ionospheric interference on the satellite signal between satellite \( s \) and position \( i \) as \( \varepsilon_i \) and applying the effect of clock errors, equation 4.11 becomes:

\[ R_s(t) = [(X_s(t) - X_i)^2 + (Y_s(t) - Y_i)^2 + (Z_s(t) - Z_i)^2]^{1/2} + c[\delta_s(t) - \delta_i(t)] + \varepsilon_i \]  

4.14

The unknown parameters to be determined in equation 4.14 are the three dimensional coordinates of the receiver position and the receiver’s clock error. There are four unknowns, hence by observing signals from at least four satellites, four systems of equations may be developed to determine these parameters.

### 4.7 Error Sources in GPS Data

GPS signal transmission and subsequent position computations from GPS data are susceptible to several sources of errors. These errors are a combination of noise and bias. Noise errors arise from satellite signal degradation in transit as well as the noise associated with the equipment. These are corrected by use of rigorous computational
techniques such as single and double differencing. The bias errors, which can only be controlled through appropriate field practices, include satellite availability, clock errors, atmospheric delays, and multi-path errors.

4.7.1 Selective Availability (SA)

Selective availability (SA) is the intentional degradation of the SPS signals by a time-varying bias, and is implemented by the US Department of Defense to limit accuracy for non-military or government users. This is done by manipulating the satellite clock (δ-process) and the satellite ephemerides (ε-process). The SA bias on each satellite signal is different, and so the resulting position solution is a function of the combined SA bias from each satellite used in the navigation solution. The accuracy of the NAVSTAR system on the PPS compared to the SPS contained in the Federal Radio-navigation Plan is shown in Table 4-2. Satellite availability errors is considerably reduced by the concept of differential GPS which is discussed further in Section 4.9.

4.7.2 Satellite and Receiver Clock Errors

The fundamental concept in the use of GPS is that time synchronization is required between the satellites being tracked and the receiver units doing the tracking. Satellite times are continuously monitored and corrections are uploaded from the master control station to all the satellites. Receiver times on the other hand contain errors associated with their clocks and are different between receivers. These errors are reduced or completely removed through computational techniques.
Table 4-2: Predictable Accuracy of the NAVSTAR GPS System

<table>
<thead>
<tr>
<th></th>
<th>(PPS) Precise Positioning Service</th>
<th>(SPS) Standard Positioning Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Accuracy</td>
<td>22 meters</td>
<td>100 meters</td>
</tr>
<tr>
<td>Vertical Accuracy</td>
<td>27.7 meters</td>
<td>156 meters</td>
</tr>
<tr>
<td>Time Accuracy</td>
<td>100 nanoseconds</td>
<td>340 nanoseconds</td>
</tr>
</tbody>
</table>
4.7.3 Multi-path Errors

These errors are caused by satellite signals that are reflected (bounced off) from objects before getting to the receiver. The GPS computation technique will treat these signals as taking a straight path. This introduces both noise and bias that cannot be effectively detected or corrected. Correct antennae mounting techniques help minimize multi-path signal errors.

4.7.4 Atmospheric (Tropospheric and Ionospheric) Delays

Temperature, pressure, and humidity changes in the lower atmosphere (troposphere), and the ionized conditions in the upper atmosphere (ionosphere) both have a significant effect on GPS satellite signals. This usually results in a signal delay that has been estimated to be as high as 70 nanoseconds. This may be reduced but cannot be completely removed.

4.8 Geometric Dilution of Precision

At least four satellites must be tracked by the receiver at the same time for three-dimensional position calculation. In the usual case, where the receiver tracks more than four satellites at the same time, it is necessary to determine which set of four satellites gives the best position fix. The guiding parameter to make this determination is called the Geometric Dilution of Precision (GDOP). The GDOP is a measure of the error contributed by the geometric relationships of the satellites as observed from the receiver position. The least error occurs when the range vectors are at right angles, and is greatest.
as the vectors approach parallel. The GDOP is calculated as the square root of the variances of position errors and time bias:

$$GDOP = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_t^2)^{1/2}$$ \hspace{1cm} 4.15

Similarly four other precision factors are defined:

Position Dilution of Precision (PDOP) = $$(\sigma_x^2 + \sigma_y^2)^{1/2}$$

Horizontal Dilution of Precision (HDOP) = $$(\sigma_x^2 + \sigma_y^2)^{1/2}$$

Vertical Dilution of Precision (VDOP) = $$(\sigma_z^2)^{1/2}$$

Time Dilution of Precision (TDOP) = $$(\sigma_t^2)^{1/2}$$ \hspace{1cm} 4.16

A smaller DOP value corresponds to better accuracy. However, the significant DOP value depends on the application; for example PDOP is the principal parameter in three-dimensional position determination.

4.9 The Concept of Differential GPS

Differential GPS (DGPS) utilizes the GPS measurement data from a stationary GPS receiver placed at a site with known coordinates (base station) to correct the errors in the measurement data of another GPS receiver at an unknown site (remote station). Where the remote receiver is in continuous motion (kinematic), it is referred to as the rover
station. The underlying principle in this approach is that the errors in the time-tagged GPS signal from a given satellite are similar over a region of approximately 500 km (Hofman-Wellenhof et al., 1997), and are common to the base and the remote stations. The correction is effected by adding similar errors in the base station data to the remote station data, based on identical time tags.

Suppose that the precise base station coordinates are $X_B$, $Y_B$, $Z_B$. At a given epoch $t$, suppose the signals from a satellite compute the base station coordinates as $X_{Bt}$, $Y_{Bt}$, $Z_{Bt}$. Now suppose that the remote station coordinates are measured as $X_{Rt}$, $Y_{Rt}$, $Z_{Rt}$. The position errors at epoch $t$ is computed in a simplified form as:

$$\Delta X = X_B - X_{Bt}$$

$$\Delta Y = Y_B - Y_{Bt}$$

$$\Delta Z = Z_B - Z_{Bt}$$

These errors are mostly due to SA and are applied to the remote station data during post processing to obtain a more accurate position of the remote receiver position as:

$$X_R = X_{Rt} + \Delta X$$

$$Y_R = Y_{Rt} + \Delta Y$$

$$Z_R = Z_{Rt} + \Delta Z$$
Four satellites are required to calculate the 3-D coordinates of a point; therefore for a base station to work effectively it must be tracking the same satellites (at least four) as the remote station at a given epoch. Two approaches are used to ensure this. In the first case, a larger tracking window is defined for the base antenna by setting its elevation mask angle lower than that for the remote antenna. Elevation mask is the mask angle above the horizon below which satellites are not tracked; a typical elevation mask setting is 10 degrees for the base station and 15 degrees for the remote station. The second approach is to mount the base station antenna at a relatively higher elevation than the remote antenna to eliminate possible signal obstructions.

In the common usage of differential GPS, both the base station data and rover station data are collected simultaneously and then post-processed at a later time to effect the correction. In real-time DGPS operation, however, the base station data is transmitted in real time to the remote station so that the correction is effected on-the-fly. Where the system is used with a kinematic rover station, it is referred to as a real-time kinematic (RTK) system. Real-time kinematic systems, though more prone to signal errors, are nonetheless desirable for those applications where correct coordinate information is needed at once. The data transfer from base station to rover station are broadcast through a radio link to both receivers.
4.10 System Components

The system setup comprises three hardware components:

1. The Dynamic measurement unit – fiber optic gyroscope (DMU-FOG)
2. The GeoResearch Workhorse GPS receiver; and
3. The Databrick data logger.

4.10.1 Dynamic Measurement Unit – Fiber Optic Gyroscope (DMU-FOG)

Cross Bow Technology’s DMU-FOG is a vertical gyroscope for angular measurement in dynamic environments. The equipment is housed and shielded in an aluminum casing 5.0” x 5.0” x 4.0”; it sits on a mounting base plate 5.0” x 6.0” x 0.125”. The base plate provides perforation for attaching the gyroscope to a support. On its rear face the gyroscope has a female DB-15 pin connector that interfaces at the serial communication port of a data logging computer. The equipment has no moving parts and is highly tolerant of vibration and shock.

The DMU-FOG utilizes three accelerometers made of surface micro-machined silicon devices to sense linear acceleration around the three orthogonal axes, and three fiber-optic gyroscopes to provide angular rate measurements. The angular rate measurements are output independently of acceleration. Older gravity-based tilt sensors use the earth’s gravitational field to measure angles, and do so accurately only when the object measured is not accelerating. In dynamic environments, such sensors cannot distinguish between tilt and acceleration. The DMU-FOG uses the combination of angular rate and
acceleration signals to overcome this problem. Angle tilt is calculated by integrating the angular rate sensor outputs to an angle value. Then the tilt response of the accelerometers corrects for error due to angular rate drift. The frequency of the drift correction updates is set by a quantity termed the *erection* or *T* setting. With a small *T* setting the rate gyros are dominant, while a large *T* setting forces the rate gyros to follow the accelerometer measurement of vertical more closely. In a dynamic environment, a low *T* setting is recommended. In this study a *T* setting of 5 was used. A test to determine the actual angular rate drift is described in Section 4.12.2.

The DMU-FOG has both an analog output and an RS-232 serial link. Data may be polled via the serial link as a single measurement, or is set for continuous transfer. The unit employs an on-board analog to digital converter and a high performance digital signal processor. Figure 4-9 shows a block diagram of the DMU-FOG signal processing method. Detailed description of the equipment specification is provided in Appendix A.

4.10.2 The DMU-FOG Coordinate System

The DMU FOG has a sticker on one face illustrating its coordinate system. With the serial connector facing the operator, and the mounting base plate down, the axes are defined as follows (see Figure 4-10):

- **x-axis**: from face with connector through the DMU-FOG.
- **y-axis**: along the face with connector from left to right.
- **z-axis**: along the face with the connector from top to bottom.
Figure 4-9: Block Diagram of DMU-FOG Signal Processing Method

Figure 4-10: DMU-FOG Orthogonal Axes Definition
The axes form an orthogonal right handed coordinate system. Measured acceleration is positive when it is oriented towards the positive side of the coordinate axis. For example with the unit sitting on a level table, it will measure zero g along the x- and y-axes, and +1 g along the z-axis. So, gravitational acceleration directed down is defined as positive.

The angular measurements are also aligned with the same axes. Angular rotation is measured around a given axis and labeled by the appropriate axis. The direction of a positive rotation is defined by the familiar right-hand rule. With the thumb of the right hand pointing along the positive direction of the axis, the fingers curl around in the positive rotation direction. Pitch is defined as positive for a positive rotation around the y-axis (the front of the vehicle comes up while facing the positive x-axis direction). Roll is defined as positive for a positive rotation around the x-axis (left side of the vehicle comes up while facing the positive x-axis direction). Yaw is defined as positive for a positive rotation around the z-axis (a right turn movement while facing the positive x-axis direction). For example, if the unit is placed on a level surface with base plate down, and it is rotated clockwise on the surface, this will be a positive yaw (rotation around the z-axis). The x- and y-axis rate sensors would measure zero angular rate, and the z-axis sensor would measure a positive angular rate.
4.10.3 GPS Receiver - The GeoResearch Workhorse

The GeoResearch Workhorse is a relatively small GPS receiver measuring about 6.0” x 4.0” x 3.25”. It is housed in a lightweight, high impact aluminum casing that can withstand normal field conditions. The Workhorse is constructed on the Motorola 8-channel Oncore receiver, with superior algorithms for satellite tracking under challenging GPS conditions such as tree canopies and urban canyons. Its 8 channels provide the optimum parallel satellite tracking number for the US but without the added complexity, micro-processor demand, and memory requirements of 12 channel receivers. It has a magnetic mount antenna that measures about 2.0” x 3.25” x 0.64”.

The Workhorse is provided with a dual serial port that can be used to interface with a data logging computer. Without satellite availability, the position accuracy is specified at less than 25 meters; with differential correction, however, the accuracy is specified as high as 2.0 to 5.0 meters. More importantly, the typical time for satellite re-acquisition is specified at 2.5 seconds. This is important as data loss with the Workhorse is minimal especially on freeways with little tree cover. Significant data loss requires supplemental field data collection; recall this was cited as one of the drawbacks of the GPS methodology developed by Awuah-Baffour, 1997. Detailed specifications of the Workhorse is given in Appendix A.
4.10.4 The Databrick Data Logger

The data logging computer used is not a critical part of the system since any computer with dual serial ports and standard software capabilities will suffice. On this project, we used a Databrick data logger manufactured by Datalux Corporation. The Databrick is a rugged computer built essentially for use in field environments; it is lightweight and low energy consuming. Its more important attribute for this research is that it has dual serial ports to which the GPS receiver and dynamic measurement instrument could be attached. It also has a parallel port to which an external zip drive can be attached to download the data.

4.11 Data Acquisition and Integration

Data acquisition with the combined GPS-Gyroscope system (GPS-Gyro combo) is handled through software programs written in National Instrument’s LabVIEW programming environment. LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a development environment based on the graphical programming language G, and is integrated fully for communication with hardware such as GPIB (General Purpose Interface Bus), VXI, RS-232, RS-485, and plug-in data acquisition boards. It is particularly useful for test and measurement, data acquisition and control, scientific research, process monitoring, and factory automation. The graphical programming environment differs from text-based programming environment in that it uses graphical symbols rather than textual language to describe programming actions.
LabVIEW programs are known as Virtual Instruments (VIs) because they imitate real instruments only that they are virtual. VIs have two parts: the front panel, and the block diagram. The front panel is the graphical user interface of the VI; it collects user input and displays program output and may contain knobs, push buttons, graphs, and other controls and indicators. Program execution is initiated, controlled, and stopped with icons on the front panel. The block diagram contains the graphical source code of the VI; this is where the VI is programmed to control and perform functions on inputs and outputs from the front panel. Both the front panel and the block diagram are created and edited using palettes. Three palette types are employed: the tool palette which gives options to edit, create, or debug both front panel and block diagram objects; the controls palette which contains controls and indicators for creating the front panel; and the functions palette which contains the objects used to program the VIs, such as arithmetic, instrument I/O, file I/O, and data acquisition operations.

LabVIEW uses a patented dataflow programming model that is different from the linear architecture of text-based languages. The execution order in LabVIEW is determined by the flow of data between blocks, and not by sequential lines of text, thus it is possible to create diagrams that have simultaneous operations. The block diagram consists of nodes and terminals from the front panel. The nodes are connected by wires, which define the flow of data through the program. The execution of a node occurs when all its inputs are available; after executing, the node releases its outputs to the next node in the data flow.
path. LabVIEW is a multitasking and multithreaded system, making it possible to run multiple execution threads and multiple VIs. This last functionality enables the simultaneous running of the GPS and gyroscope and acquisition of their data output from the computer’s serial ports.

4.12 System Setup and Instrumentation

The system instrumentation comprises two different setups: the first setup is referred to as the system calibration setup, and is used for evaluating and calibrating the gyroscope output data; the second setup is the data collection setup, and is used for collecting the integrated GPS and gyroscope data.

4.12.1 Procedure and Setup for System Calibration

The system calibration setup is shown in Figure 4-11. Basically, the gyroscope is connected to the serial port of a data logging computer. The system calibration model is developed from data collected with this setup; the data analysis for developing the calibration model forms the major portion of Chapter V. The software program that runs this set up is a proprietary LabVIEW program called X-VIEW from Cross Bow Technologies. The step-by-step procedure for collecting calibration data is given in Chapter VI.
Figure 4-11: Set-up for System Calibration
The methodology for developing the system calibration model requires a procedure that permits direct comparison of the gyroscope road grade data against a range of accurately measured road grades. X-view incorporates this important functionality by permitting the operator to insert tags in the data stream. Table 4-3 is an example header output file from the DMU-FOG obtained with X-VIEW. The file comprises 12 fields of which the important ones for the purposes of this research are the pitch field (column 3) and the tag field (column 12): the pitch field defines the road grade output as measured by the gyroscope, while the tag field contains the tag numbers inserted by the operator during data collection to identify the points in the data stream corresponding to stations along the road with known grades.

Multiple grade data was collected on road segments incorporating grade values in the range of +14.6% to -14.6%. This rather wide range of grade was initially selected so as to broaden the applicability of the calibration model that is developed. However, by specification, the grade on freeways and major arterial roads is typically in the range of +6.0% to -6.0%. For ease of analysis, three road segments incorporating three grade classifications were delineated as follows:

- Road segment incorporating *high* grade in the range ± 14.6%
- Road segment incorporating *medium* grade in the range ± 10.5%, and
- Road segment incorporating *level* grade in the range ± 2.0%.

On each road segment type, a series of stations were staked out with suitable distances (typically 25 ft.) between them, and the actual grade at the stations were measured by a
Table 4-3: Example Header of the DMU-FOG Output File

<table>
<thead>
<tr>
<th>Time</th>
<th>Roll (deg)</th>
<th>Pitch (deg)</th>
<th>Roll Rate (deg/sec)</th>
<th>Pitch Rate (deg/sec)</th>
<th>Yaw Rate (deg/sec)</th>
<th>X Accel (G)</th>
<th>Y Accel (G)</th>
<th>Z Accel (G)</th>
<th>Temp Sensor (C)</th>
<th>Timer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-2.225</td>
<td>-2.873</td>
<td>0.357</td>
<td>-0.041</td>
<td>-0.563</td>
<td>0.128</td>
<td>-0.107</td>
<td>2.574</td>
<td>39.116</td>
<td>0.039</td>
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<td>0.034</td>
<td>-2.219</td>
<td>-2.845</td>
<td>0.119</td>
<td>0.298</td>
<td>-0.082</td>
<td>0.156</td>
<td>-0.178</td>
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<td>39.061</td>
<td>0.05</td>
</tr>
<tr>
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<td>-0.403</td>
<td>-0.096</td>
<td>-0.375</td>
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<td>39.17</td>
<td>0.015</td>
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<td>-2.829</td>
<td>0.504</td>
<td>0.348</td>
<td>-0.032</td>
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<td>-0.157</td>
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<td>39.17</td>
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<td>39.17</td>
<td>0.043</td>
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<tr>
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<td>0.311</td>
<td>-0.179</td>
<td>-0.082</td>
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<td>0.003</td>
<td>-0.191</td>
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<td>0.048</td>
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<td>-2.829</td>
<td>0.119</td>
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<td>0.195</td>
<td>-0.079</td>
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<td>39.061</td>
<td>0.019</td>
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<td>0.06</td>
<td>0.009</td>
<td>0.101</td>
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<td>2.409</td>
<td>39.007</td>
<td>0.042</td>
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<td>-2.807</td>
<td>0.266</td>
<td>0.105</td>
<td>0.105</td>
<td>0.123</td>
<td>-0.096</td>
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<td>39.116</td>
<td>0.018</td>
</tr>
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<td>-2.812</td>
<td>-0.357</td>
<td>0.05</td>
<td>-0.133</td>
<td>0.007</td>
<td>-0.092</td>
<td>2.301</td>
<td>39.17</td>
<td>0.047</td>
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<tr>
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<td>-2.758</td>
<td>-0.069</td>
<td>0.531</td>
<td>-0.275</td>
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<td>-0.178</td>
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<td>39.061</td>
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<td>-0.275</td>
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<td>-0.104</td>
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<td>39.17</td>
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<td>0.218</td>
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<td>2.403</td>
<td>39.17</td>
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<td>-0.119</td>
<td>0.142</td>
<td>-0.467</td>
<td>0.219</td>
<td>-0.07</td>
<td>2.485</td>
<td>39.116</td>
<td>0.039</td>
</tr>
<tr>
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<td>-2.692</td>
<td>-0.307</td>
<td>0</td>
<td>-0.087</td>
<td>0.114</td>
<td>-0.158</td>
<td>2.355</td>
<td>39.17</td>
<td>0.016</td>
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<tr>
<td>0.508</td>
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<td>-2.666</td>
<td>0.22</td>
<td>-0.032</td>
<td>0.105</td>
<td>0.239</td>
<td>0.016</td>
<td>2.418</td>
<td>39.116</td>
<td>0.039</td>
</tr>
<tr>
<td>0.532</td>
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<td>-2.675</td>
<td>0.407</td>
<td>-0.087</td>
<td>-0.32</td>
<td>0.263</td>
<td>-0.052</td>
<td>2.487</td>
<td>39.116</td>
<td>0.015</td>
</tr>
<tr>
<td>0.556</td>
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<td>-2.664</td>
<td>0.027</td>
<td>0.055</td>
<td>0.055</td>
<td>0.124</td>
<td>-0.171</td>
<td>2.599</td>
<td>39.116</td>
<td>0.044</td>
</tr>
<tr>
<td>0.615</td>
<td>-2</td>
<td>-2.67</td>
<td>0.215</td>
<td>0.105</td>
<td>-0.037</td>
<td>0.138</td>
<td>-0.124</td>
<td>2.453</td>
<td>39.116</td>
<td>0.021</td>
</tr>
</tbody>
</table>
grade master. The grade master is a manual level, about 4.0 feet long, with a calibrated grade measurement ruler at one end. The grade master is placed longitudinally along the centerline of the road at a station, and after the bubble is leveled, the grade severity at that station is read off of the calibrated ruler. Now, with the gyroscope mounted in a vehicle, the vehicle is driven along the road segment. At the point when the vehicle passes each station, a marker is placed in the data stream to identify the gyroscope reading at that station. Subsequently, the value of the gyroscope output at that point is compared to the actual grade reading recorded with the grade master for the station. Numerous such data was collected on the three road segments and this data was used to develop the gyroscope output calibration model. However, from subsequent data analysis performed in Chapter V for the development of the calibration model, the model scope was reduced to road grade in the range of +10.5% to -10.5%. The rationale for doing so is explained in Chapter V.

4.12.2 Preliminary Evaluation of the Gyroscope Data

In assessing the capability of the gyroscope, three questions were confronted: the first was to assess the initial bias of the gyroscope output, the second was to determine the effect of the vehicle suspension on the data, and the third was to determine the rate of angular drift over time. When the gyroscope is placed on a level surface the pitch does not necessarily read a constant zero, rather it gives values that center about zero. A test was developed to determine if the readings are skewed either negative or positive, which would be the initial instrument bias. Also, uneven road surface creates vehicle
suspension deflections that could affect the gyroscope output. When a vehicle goes over a bump or into a pothole, the sudden deflection of the vehicle suspensions throws the vehicle chassis (and the orientation of the gyroscope) off from following the actual road grade alignment. This introduces errors into the data that could potentially saturate the actual instrument output.

To analyze the first two effects, an initial test was performed where the gyroscope was isolated from vibrations and vehicle suspension effects. This was accomplished by attaching it on a rigid suspension hand wagon as shown in Figure 4-12. The wagon was placed on a level (approximately 0.0% grade), carpeted surface and subjected to accelerations and decelerations. Analysis of this data showed no initial bias; the readings were either positive or negative, with the average centered around zero. More than 75% of the data on this 0.0% grade fall within ± 0.5 but the entire range is +1.296 to −1.35. This means that even on a level surface, the gyroscope output error can be expected to fluctuate in that range. In effect, this can be defined as the bias limits for the instrument.

The hand wagon was also pulled along road segments at walking pace, and readings were taken at different stations to determine what effect the absence of vehicle suspension errors will have on the output. The result is shown graphically as Figure 4.13. Without vehicle suspension bias, the instrument reading is similar for both positive and negative grade orientation. This is important as subsequent readings when the instrument is mounted in a vehicle shows a difference in upgrade and downgrade readings. This is discussed as part of the data analysis exercise presented in Chapter V.
Figure 4-12: Gyroscope Set-up in Hand Wagon to Determine Initial Bias, and the Effect of Vehicle Suspension.
Figure 4-13: Comparison of Actual Grade, Upgrade Reading, and Downgrade Reading in the Absence of Vehicle Suspension Effects.
In the test to determine the amount of angular rate drift, a set of 9 stations approximately 25 feet apart were established on a road section. A vehicle with the gyroscope mounted in it was driven along the road section and the gyroscope reading at each station was taken. This was repeated, with the gyroscope running continuously, at intervals of approximately 30 minutes for 3 hours for a total of 7 readings at each station. The results are shown in Table 4-4 along with the actual measured grade at the stations, and graphically in Figure 4-14.

Had the gyroscope output been subject to significant drift, it was expected that the difference in the readings at each station over time would show a steady increasing (decreasing) pattern that can be quantified. This can then be distributed as a function of the time over which the gyroscope had continuously been in use. Table 4-5 shows the variation over time in the gyroscope readings (compared to the initial reading taken after the equipment was turned on) at the nine stations. This is also shown graphically in Figure 4-15 where the x-axis is the time over which the gyroscope had been in use, and the y-axis represents the difference in the gyroscope reading. Each graph represents the time-varying difference in the reading at a station. As stated above, a drift in the gyroscope would be reflected by a continuous rise (or fall if the drift is negative) with time in each graph. This is not the case; the variation at every station appears to be random across time.
Table 4-4: Gyroscope Reading Over Time to Determine Angular Rate Drift (Numbers in Run Headers Denote Elapsed Time in Minutes)

<table>
<thead>
<tr>
<th>Station</th>
<th>Grade (%)</th>
<th>Run1</th>
<th>Run35</th>
<th>Run60</th>
<th>Run90</th>
<th>Run120</th>
<th>Run150</th>
<th>Run180</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-7</td>
<td>-2.9</td>
<td>-3.296</td>
<td>-3.115</td>
<td>-3.186</td>
<td>-3.186</td>
<td>-2.984</td>
<td>-2.952</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.472</td>
<td>0.805</td>
<td>0.485</td>
<td>0.77</td>
<td>0.612</td>
<td>0.504</td>
<td>0.497</td>
</tr>
<tr>
<td>9</td>
<td>5.75</td>
<td>3.972</td>
<td>4.208</td>
<td>3.735</td>
<td>4.422</td>
<td>3.994</td>
<td>3.983</td>
<td>4.146</td>
</tr>
</tbody>
</table>

Figure 4-14: Graphical Presentation of Gyroscope Reading Over Time
Table 4-5: Variation in Gyroscope Reading Over Time (Compared to Initial Reading)

<table>
<thead>
<tr>
<th>Station</th>
<th>Elapsed Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Station 1</td>
<td>0.033</td>
</tr>
<tr>
<td>Station 2</td>
<td>-0.396</td>
</tr>
<tr>
<td>Station 3</td>
<td>-0.335</td>
</tr>
<tr>
<td>Station 4</td>
<td>-0.351</td>
</tr>
<tr>
<td>Station 5</td>
<td>0.333</td>
</tr>
<tr>
<td>Station 6</td>
<td>-0.511</td>
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<td>Station 7</td>
<td>-0.176</td>
</tr>
<tr>
<td>Station 8</td>
<td>-0.115</td>
</tr>
<tr>
<td>Station 9</td>
<td>0.236</td>
</tr>
</tbody>
</table>

Figure 4-15: Graphical Presentation of the Variation in Gyroscope Reading Over Time (Compared to Initial Reading)
4.12.3 Procedure and Setup for Data Collection

The data collection setup is depicted in Figure 4-16; here the GPS receiver and the gyroscope are each connected to one of the computer's serial ports. The GPS receiver is connected to Com Port 1 while the gyroscope is connected to Com Port 2. With this setup, the actual integrated GPS and gyroscope grade data for the roadway are collected. The software program that runs this setup is a LabVIEW program comprising four separate VIs developed specifically for this purpose. A description of the VIs is provided in Section 4.12.4 below, and the step-by-step procedure for collecting the integrated grade data is provided in Chapter VI.

4.12.4 Integrating Grade and Coordinate Data

The integration of the gyroscope grade data and the GPS coordinate data is achieved through these four VIs running simultaneously, namely:

(i) Log WHII.vi: This VI collects GPS data from serial port 1 and stores them in a Motorola binary file (.pdr) format. The file so created contains the spatial data for locating the grade data. The Motorola binary file format is used because the post processing software is based on this file format.

(ii) WH position-status.vi: This VI gives a text-based and readable screen display of the GPS data. It does not log to a file, rather it allows the operator to see the real-time status of the GPS signals.
Figure 4-16: Set-up for Simultaneous Grade and Position Data Collection
(iii) DMU Example.vi: This VI logs the gyroscope road grade data from serial port 2. It does not log to a file, but gives a screen display of the real time status of the grade data.

(iv) Gps-gyro-combo.vi: This is the main control VI that interfaces with the other three VIs. Specifically, it reads in GPS time data from the Log WHII.vi and tags this information to the grade data from the DMU Example.vi. The GPS time-tagged grade data is then written to a text file.

The integration of the grade data and the position coordinate data by the Gps-gyro-combo.vi is accomplished through the unique time stamp associated with the GPS data. The GPS receiver outputs data at the rate of 1 hertz, while the gyroscope outputs data at a maximum rate of 100 hertz. Initial tests had shown that at typical vehicle speeds, this high rate of gyroscope data output would swamp and blur the spatial separation between the data points. Instead, the gyroscope was set to output data at 10 hertz, providing more distinct and meaningful separation between the data points. Table 4-6 shows example headers of the GPS output file. For the purposes of this research, the important fields in Table 4-6 are the longitude field (column 2), the latitude field (column 3), and the time field (column 4): the time is shown again in columns 5, 6, and 7 in hours, minutes, and seconds, respectively. The identified important fields are shaded gray in the table. The time field is important because it is used for matching the gyroscope data with the coordinate data, while the latitude and longitude fields are important because they define the position coordinates.
The Gps-gyro-combo.vi simultaneously reads the time field in a GPS data packet at an epoch from one serial port, and the sequence of incoming gyroscope data packets from the second serial port, and associates each gyroscope data packet with the GPS time stamp. Given the difference in the frequency of data output between the GPS and gyroscope, typically a sequence of ten gyroscope data outputs are associated with each GPS time stamp. Table 4-7 shows example headers of the Gps-gyro-combo.vi output. The file headers are basically the same as the gyroscope output of Table 4-3, but with a "GPS Time" field added to it. The "GPS Time" is the common field between the spatial data (longitude, latitude) of Table 4-6 and the road grade data (pitch) of Table 4-3, and is used to locate the coordinates of each of the grade data. Before locating the coordinates of the grade data, the following two tasks must be completed:

(i) post-processing (differential correction) of the spatial data, and
(ii) screening of the grade data.

The procedures for both tasks and for locating the grade coordinate data are discussed in the sections below.

4.12.4.1 Post-Processing the Spatial Data:

Post-processing is used to eliminate the errors associated with selective availability. The program that runs this procedure is a proprietary software from GeoResearch, Inc. called PostPoint; it is based on the Motorola binary (.pdr) file format. However, the GPS base station receiver that supplied the correction base file is an Ashtech Z12 which has its file in the Ashtech file format. Thus, to use the base station file with PostPoint, the file is

first converted to the Receiver Independent Exchange (RINEX) file format, and then converted to the Motorola binary file format. Collecting the GPS base station file and converting it to RINEX format is accomplished with an Ashtech proprietary software called PRISM. The procedures for doing both tasks are contained in the PRISM Users Manual and is not repeated here. Converting the base station file from RINEX format to Motorola format, and then using it to post process the spatial data is done with the PostPoint software. The procedure for both tasks is contained in the PostPoint Users Manual and is also not repeated here. The post-processed spatial file has the same format as shown in Table 4-6.

4.12.4.2 Screening the Grade Data:

Screening of the grade data basically involves reducing the data to only the values that fall within the model scope. The calibration model developed in Chapter V is applicable to road grade in the range of +10.5% and -10.5%, with a corresponding gyroscope reading in the range of +7.361 and -6.278, respectively. The justification for limiting the model scope to this data range is provided in Section 5.4.3. Recall, however, that road grade above 7.0% is hardly encountered on freeways, arterial roads, or other major roadways where this equipment is most likely to be used. A computer program, written in PERL, performs the operation, and the description is provided in Appendix B.
4.12.4.3 Locating Coordinates of the Grade Data:

This task is accomplished by a PERL computer program termed \textit{match-gps-gyro.pl}. The method used essentially interpolates the difference in the coordinates (longitude and latitude) of two consecutive GPS epochs between the intervening grade data points that have the same time stamp as the first GPS epoch. To further explain how this works, refer to Table 4-6 and Table 4-7 for example. In Table 4-6, the first GPS epoch (first data row) is 0, 29, 02 (for hour, minute, and second, respectively), and the second GPS epoch is 0, 29, 03. In Table 4-7, the first six grade data (first six rows) have the "GPS Time" of 0:29:02 (for hour: minute: second). These are the sequence of grade data that are associated with that GPS time and, by extension, the coordinates at that epoch. The seventh row in Table 4-7 has the "GPS Time" of 0:29:03. The program interpolates the difference in the coordinate data at epoch 0:29:02 and epoch 0:29:03 in Table 4-6 and allocates the values, in proportion to the order of occurrence, as the coordinates of the intervening six grade data points in Table 4-7.

Thus, the resulting data file from this process will have coordinates of 84.504525278°, 33.689766389° (longitude, latitude) and 84.504526667°, 33.689768056° for the first and the seventh grade data points, respectively. The difference between these two coordinates is interpolated to locate the coordinates of the intervening five grade data points between them. This process is repeated from one epoch to the next to locate the coordinates of all grade data points, using values from Table 4-6 and Table 4-7. Both the longitude and latitude values are given in degrees, minutes, seconds and decimal seconds.
to eleven decimal places. That degree of precision is necessary to establish a meaningful separation between the data points.

4.12.4.4 Application of the Calibration Model to the Grade Data:

The values in the “Pitch” field in Table 4-7 represents the raw gyroscope output. These are converted to percentage grade values (rise over run) by application of the calibration model developed in Chapter V. This process is accomplished by a PERL program called Model.pl with description and code provided in Appendix B. Basically, the program converts each pitch reading according to the model and gives the output as a percentage grade value to two decimal places.

Automation of the procedures described in this section have been accomplished using four computer programs written in PERL. The codes for all four programs are provided in Appendix B. For convenience, the programs are restated here:

(i) Clean-gps.pl: this formats the post-processed GPS data so that it can be used to match the cleaned gyroscope grade data.

(ii) Clean-gyro.pl: this formats the gyroscope grade data so that it can be used to match with the GPS data.

(iii) Match-gps-gyro.pl: this locates the coordinates of each grade data point by matching it with the GPS data and interpolating in between.
(iv) Models.pl: this screens the gyroscope data to eliminate values outside the model scope, and then applies the calibration model to convert each raw gyroscope reading to a percentage grade value.

(v) Batch.pl: this manages the other three programs.

The batch.pl program controls and manages the other three programs. In this multi-program procedure, where the output of one program serves as input to another, the value of the batch program is that it takes the specification of input/output files away from the operator and automates the process. Thus, all the operator needs to specify as input are the post-processed spatial GPS file (example Table 4-6), the GPS Time-tagged grade file (example Table 4-7), and the name of an output file. The rest of the process is automatically executed to give the final spatially resolved grade data output file. The step-by-step procedure for running the programs is presented in Chapter VI.

An example of the final grade output file is shown as Table 4-8. The table contains only fields that define the road grade (Grade), the coordinates (Longitude, Latitude), and an identification number (ID) that denotes the sequence of occurrence of the data points in the direction of travel along the road.

The calibration model is developed for the gyroscope in a particular vehicle, therefore the model is applicable only to grade data collected with the same vehicle. If a different vehicle is used, a different calibration model will need to be developed. While the model cannot be used with a different vehicle, the methodology developed in this research can
Table 4-8: Sample of Final Spatially-Resolved Road Grade Data File

<table>
<thead>
<tr>
<th>ID</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33:41:24.76899999996</td>
<td>84:30:12.663</td>
<td>0.70</td>
</tr>
<tr>
<td>2</td>
<td>33:41:24.43859999988</td>
<td>84:30:13.38720000012</td>
<td>0.73</td>
</tr>
<tr>
<td>3</td>
<td>33:41:24.1082000000016</td>
<td>84:30:14.111399999988</td>
<td>0.70</td>
</tr>
<tr>
<td>4</td>
<td>33:41:23.7778000000008</td>
<td>84:30:14.8356</td>
<td>0.72</td>
</tr>
<tr>
<td>5</td>
<td>33:41:23.4474</td>
<td>84:30:15.559800000012</td>
<td>0.72</td>
</tr>
<tr>
<td>6</td>
<td>33:41:23.11699999992</td>
<td>84:30:16.283999999988</td>
<td>0.74</td>
</tr>
<tr>
<td>7</td>
<td>33:41:23.117399999988</td>
<td>84:30:16.2846</td>
<td>0.76</td>
</tr>
<tr>
<td>8</td>
<td>33:41:23.11779999994</td>
<td>84:30:16.285200000012</td>
<td>0.73</td>
</tr>
<tr>
<td>9</td>
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<td>84:30:16.285799999988</td>
<td>0.72</td>
</tr>
<tr>
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</tr>
<tr>
<td>11</td>
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<td>84:30:16.287000000012</td>
<td>0.71</td>
</tr>
<tr>
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<td>84:30:16.28683333344</td>
<td>0.72</td>
</tr>
<tr>
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<td>84:30:16.286666666676</td>
<td>0.70</td>
</tr>
<tr>
<td>14</td>
<td>33:41:23.119500000012</td>
<td>84:30:16.286500000008</td>
<td>0.68</td>
</tr>
<tr>
<td>15</td>
<td>33:41:23.11966666668</td>
<td>84:30:16.2863333334</td>
<td>0.66</td>
</tr>
<tr>
<td>16</td>
<td>33:41:23.11983333348</td>
<td>84:30:16.286166666672</td>
<td>0.62</td>
</tr>
<tr>
<td>17</td>
<td>33:41:23.120000000016</td>
<td>84:30:16.286000000004</td>
<td>0.58</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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<td>84:30:16.28349999984</td>
<td>0.55</td>
</tr>
<tr>
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<td>84:30:16.28266666668</td>
<td>0.57</td>
</tr>
<tr>
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<td>84:30:16.2818333334</td>
<td>0.61</td>
</tr>
<tr>
<td>23</td>
<td>33:41:23.12099999988</td>
<td>84:30:16.281</td>
<td>0.62</td>
</tr>
<tr>
<td>24</td>
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<td>84:30:16.282400000004</td>
<td>0.63</td>
</tr>
<tr>
<td>25</td>
<td>33:41:23.122600000008</td>
<td>84:30:16.283800000008</td>
<td>0.62</td>
</tr>
<tr>
<td>26</td>
<td>33:41:23.1234</td>
<td>84:30:16.285200000012</td>
<td>0.63</td>
</tr>
<tr>
<td>27</td>
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<td>84:30:16.2865999998</td>
<td>0.64</td>
</tr>
<tr>
<td>28</td>
<td>33:41:23.12499999984</td>
<td>84:30:16.28799999984</td>
<td>0.61</td>
</tr>
<tr>
<td>29</td>
<td>33:41:23.124400000008</td>
<td>84:30:16.288400000016</td>
<td>0.62</td>
</tr>
<tr>
<td>30</td>
<td>33:41:23.12379999996</td>
<td>84:30:16.288800000012</td>
<td>0.63</td>
</tr>
<tr>
<td>31</td>
<td>33:41:23.12319999984</td>
<td>84:30:16.289200000008</td>
<td>0.64</td>
</tr>
<tr>
<td>32</td>
<td>33:41:23.122600000008</td>
<td>84:30:16.289600000004</td>
<td>0.67</td>
</tr>
<tr>
<td>33</td>
<td>33:41:23.12199999996</td>
<td>84:30:16.1629</td>
<td>0.70</td>
</tr>
<tr>
<td>34</td>
<td>33:41:23.1233333334</td>
<td>84:30:16.2891666666</td>
<td>0.72</td>
</tr>
<tr>
<td>35</td>
<td>33:41:23.12466666684</td>
<td>84:30:16.2883333332</td>
<td>0.74</td>
</tr>
</tbody>
</table>
be generalized and used to develop calibration models with other vehicles. The
development of the calibration model with the vehicle used in this research is discussed
in Chapter V.
CHAPTER V

DATA ANALYSIS AND DEVELOPMENT OF
THE GYROSCOPE CALIBRATION MODEL

The goal of this research is to develop a methodology capable of measuring roadway grade in kinematic mode. In doing so, the research will yield a method capable of developing a database of spatially-referenced grade data. Because of the measurement errors inherent in the grade data, a statistical approach to the data analysis was adjudged most appropriate. The subject of this chapter is to present and justify the statistical methods employed in the data analysis and to detail the estimation of the calibration model used to resolve the raw gyroscope data to accurate and usable grade data.

A previous study by Wolf et al. (1999) had established the accuracy of the Workhorse GPS receiver, so a supplemental analysis of GPS data accuracy was not conducted as part of this research effort. Instead, the bulk of the data analysis effort here is focused primarily on the roadway grade data from the DMU-FOG. First, the proposed theoretical model for the data is presented, followed by a description of the statistical methods adopted here, its underlying assumptions, and limitations. Finally the development of the calibration model for the gyroscope data is presented.
5.1 Proposed Theoretical Model

In Section 3.2 it was explained that this research was based on the hypothesis that the integrated output of a fiber optic gyroscope and a GPS receiver can be used to simultaneously determine the grade at a point on a roadway and the coordinates of the point. It was hypothesized that the gyroscope output can be statistically modeled to give repeatable measurement of roadway grade. From this hypothesis, the proposed theoretical model is stated as follows:

\[
\text{Grade (\%) = (Gyroscope Reading) + Errors} \quad 5.1
\]

The theoretical background that established this relationship was presented in Chapter IV. In addition, the error associated with the gyroscope reading is a function of factors three of which are presently stated:

- vehicle suspension deflection,
- road surface unevenness, and
- lagged measurement dependence.

Stated formally:

\[
\text{(Gyroscope Error) = } f(\text{vehicle suspension deflection, road surface unevenness, lagged measurement dependence}) \quad 5.2
\]
A scatter plot of the gyroscope output (Reading) was plotted against the actual measured roadway grade in Figure 5-1. This enables a visual examination of the form of relationship between the grade and gyroscope reading which, in turn, helps inform the appropriate statistical methodology to adopt in the data analysis. The form of Figure 5-1 suggests a linear relationship, and so a simple linear regression utilizing ordinary least squares (OLS) procedures is adopted to analyze the gyroscope output.

5.2 Sources of Errors in the Gyroscope Output

The proposed theoretical model (Equations 5.1 and 5.2) stipulates that the gyroscope output is affected by a number of factors. It was reasoned that since the gyroscope is fixed to the vehicle chassis and kept level with the horizontal plane when it is initialized at zero, any extraneous disturbance and perturbation which causes the vehicle chassis to deviate from following the actual slope of the roadway would introduce errors into the data. Conditions which have been identified as potentially having such effect include sharp vehicle accelerations, potholes, bumps, and general road surface unevenness.

It would be desirable to explicitly include these factors as explanatory variables in the model; however, with the available instrumentation used in this research, the factors are either uncontrollable or un-measurable. The practical effects are transmitted as deflections in the vehicle's suspensions and reflected in the grade data as errors. As a result, for example, the gyroscope output for a long section of road with a constant
slope would, nonetheless, show some variations in the grade data for individual points. More importantly, at bumps and potholes where the reaction of the vehicle’s suspensions can cause a significant change in the chassis orientation, the data at these points will be significantly different from the general trend of the data for adjacent points, the sign depending on whether the vehicle is tipped upwards or downwards. In such cases, the magnitude of the errors may be such that the data points can be identified as outliers.

Another source of error in the data stems from spatial correlation. When data are collected over time or space, the tendency exists for the errors to be a function of a previous reading. This lagged measurement dependence is termed spatial correlation and is discussed further in Sub-section 5.3.2. A formal test (the Durbin-Watson Test) was used to establish this dependence, and remedial measures were taken accordingly.

5.3 **Linear Regression Models**

The simple linear regression model with one predictor variable is of the form:

\[ Y_i = \beta_0 + \beta_1 X_i + \epsilon_i \]  \hspace{1cm} (5.3)

where: \( X_i \) is the value of the predictor variable at the \( i \)th level;

\( Y_i \) is the value of the response variable at the \( i \)th level of the predictor variable;

\( \beta_0 \) and \( \beta_1 \) are the model parameters (also called regression coefficients); and

\( \epsilon_i \) is a random error term.
The regression function is then given by:

\[ E[Y_i] = \beta_0 + \beta_1 X_i \]  \hspace{1cm} 5.4

With sample estimators \( b_0 \) and \( b_1 \) for the model parameters, the fitted value of the response variable at the \( i \)th trial, \( Y_{(p)} \), is given by:

\[ Y_{(p)} = b_0 + b_1 X_i \]  \hspace{1cm} 5.5

And the corresponding estimated error term, \( e_i \), is given by:

\[ e_i = Y_i - Y_{(p)} \]  \hspace{1cm} 5.6

With regard to this analysis, therefore, the appropriate relationship that corresponds to Equation 5.5 is stated as:

\[ \text{Grade} (\%) = b_0 + b_1 \times (\text{Gyroscope Reading}) \]  \hspace{1cm} 5.7

Data for developing the model are generated from observations on the response variable at different levels of the predictor variable, and the task is then to estimate the model parameters \( b_0 \) and \( b_1 \) from the data. This corresponds to the observations of gyroscope
outputs taken at different values of actual roadway grades. The procedure used to generate this data was described in Chapter IV.

The interpretation of regression model 5.3 is that there is a yet unknown probability distribution of the response variable $Y$ at every level of the predictor variable $X$. The regression line connects the mean of the distributions of $Y$ at all levels of $X$ within the range of the model data. Any observed value of the response variable is thus considered a random selection from the distribution at that level of the predictor variable. The model parameter $\beta_i$ represents the change in the response variable for a unit change in the predictor variable; and $\beta_0$ is the intercept of the regression line when the response variable is equal to zero.

### 5.3.1 Properties and Limitations of the Linear Model

In using linear models, some criteria for judging what regression line fits the data “best” must be established. In other words, certain characteristics are desired of the model parameter estimators for it to be considered adequate; these include (Sachs, 1984):

1. **Unbiased**: the expected value of the estimator should equal the population value.

2. **Consistency**: the value of the estimator should converge to the population value with increasing number of observations.

3. **Efficiency**: the variance of the sampling distribution should be the minimum among all samples of equal size.
4. Sufficiency: no statistic of the same kind may provide further information about the parameter. That is, it should contain all the information that the sample provides with respect to the parameter.

5. Robustness: it should be relatively insensitive to departures from the assumed underlying distribution.

Estimators that meet these five criteria are described as Best Linear Unbiased Estimators (BLUE). In order for an estimator to be termed BLUE, it must exhibit the following properties (Granger et al., 1995):

1. $\varepsilon_i \sim N(0, \sigma^2)$: the residuals are independent and approximately normally distributed.

2. $E[\varepsilon_i] = 0$: the residuals have a mean equal to zero.

3. $E[\varepsilon_i^2] = \sigma^2$: the residuals have the same (constant) variance.

One of the estimation methods meeting the BLUE criteria, and adopted in this analysis, is the ordinary least squares procedure (OLS). The objective of the OLS procedure is to give estimators of the regression coefficients, $\beta_i$, such that the error sum of squares (SSE) between values of the response variable predicted by the regression line, $Y_{(p)}$, and the observed values, $Y_i$, is minimized; that is:

$$SSE = \Sigma (Y_i - Y_{(p)})^2$$

is a minimum.
If all the $Y_i$ observations fall exactly on the fitted regression line, then SSE is zero; and the greater the deviations of the $Y_i$ observations around the fitted regression line, the larger the SSE. Thus SSE is a measure of the variation in the $Y_i$ observations and can provide an assessment of the regression model. However, by definition SSE can only increase as the number of observations (sample size) increases. For a predictive model, therefore, a more useful statistic for assessing the variation in the $Y_i$ divides SSE by the sample size (or more appropriately, the number of degrees of freedom associated with it), and is termed the mean square error (MSE); it is defined as:

\[ MSE = \frac{SSE}{n-2} = \frac{\sum e_i^2}{n-2} \]

5.9

The smaller the MSE, the more accurate the predictive ability of the model since the deviations from the regression line are minimized. The number of degrees of freedom, $v$, of a statistic is defined as the number of independent observations in the sample (sample size, $n$) minus the number of population parameters, $K$, which must be estimated from the sample observations.

\[ v = n - K \]

5.10
The SSE has n-2 degrees of freedom associated with it; two degrees of freedom are lost because in estimating the fitted values, \( Y_{(p,k)} \), the model parameters \( \beta_0 \) and \( \beta_1 \) are estimated from \( b_0 \) and \( b_1 \), respectively.

The least squares estimate of the regression parameters for a simple linear model is obtained by solving the *normal equations*:

\[
\begin{align*}
\Sigma Y_i &= nb_0 + b_1 \Sigma X_i \quad &5.11a \\
\Sigma X_i Y_i &= b_0 \Sigma X_i + b_1 \Sigma X_i^2 \quad &5.11b
\end{align*}
\]

A measure of the degree of linear relationship between the response variable and the predictor variable is given by the *coefficient of determination*, \( R^2 \); this quantity expresses the ratio of the variation in \( Y_i \) that is explained by the regression line to the total variation in the data (Montgomery and Runger, 1994). Stated differently, \( R^2 \) is the ratio of the *regression sum of squares* to the *total sum of squares* and is given as:

\[
R = \frac{SSR}{SSTO} = \frac{\sum (Y_i - Y_{(p,k)})^2}{\sum (Y_i - Y_{(avg)})^2}
\]

5.12

If the regression explains none of the variation in the data, then \( R^2 = 0 \); if all the variation is explained, then \( R^2 = 1 \). Thus, the coefficient of determination affords a convenient way of assessing the goodness of fit of a regression model: the closer the value is to one,
the better the model. But, because it is a relative quantity (how large SSR is relative to SST), a large \( R^2 \) value may not necessarily indicate a good regression fit. Sample to sample variability very often compounds the direct use of \( R^2 \) by itself to adjudge the strength of a regression relation, hence caution need be exercised in its interpretation. However, when large \( R^2 \) values are accompanied by an index incorporating effect size, such as a small MSE, then large \( R^2 \) values could be interpreted as an indication of the goodness of fit of the model to the data.

In this analysis, in addition to MSE and \( R^2 \) values, formal F-tests for the goodness of fit of the regression line is evaluated for the selected models. The F-test involves partitioning of the error sum of squares into two components (Montgomery and Runger, 1994):

\[
SSE = SSPE + SSLF
\]

5.13

where:

- **SSPE** is the sum of squares attributable to *pure error*, and
- **SSLF** is the sum of squares attributable to the *lack of fit* of the model.

It compares the *lack of fit mean square* (MSLF) to the *pure error mean square* (MSPE) to give a measure of the regression fit. A large positive value of F-statistics indicates a good model fit. Calculation of SSPE uses repeated measurements of the response variable \( Y_i \) at given levels of the predictor variable \( X_i \). This is particularly applicable to the grade data since we have repeated readings at various grade values.
5.3.2 Deviations from the Linear Model Assumptions

In many practical cases the assumptions on the model residuals are violated. However with *robust* techniques, moderate departures from the assumptions can be accommodated without drastically affecting the validity of the model results. Two type of violations adjudged relevant to this analysis - specification errors and autocorrelation - are now discussed.

5.3.2.1 Specification Errors:

Perhaps the most important condition in building a model is the requirement that the model be correctly specified, i.e., the model adequately and correctly describes the behavior of the data. In many practical applications, the correct model is not precisely known and may therefore be incorrectly specified. This is particularly true of large multivariate data and may come about in a number of ways: first, some independent variables that contribute to the structure in the data may not have been included in the model; it is also possible to have used the incorrect functional forms of some independent variables. Alternatively, too many, hence irrelevant, independent variables may have been included in the model in an attempt to avoid specification errors. It has been shown that omission of relevant terms in the regression model causes the residual mean square to be inflated and the coefficient estimates to be biased (Freund and Minton, 1979). On the other hand, inclusion of irrelevant variables yields inefficient parameter estimates.
In this analysis, there is only one predictor variable (the raw gyroscope data) which is used as a linear predictor of the road grade. The vehicle suspensions, through their interaction with the road surface conditions, was identified as potentially having an effect on the data. However, this effect was uncontrollable and not readily measurable, and was therefore modeled as a part of the error term $e_i$.

Objective methods for ascertaining the existence of specification errors use a priori knowledge of the "true" error variance, usually as results from previous experiments. A more subjective method, which requires no prior information, uses the plot of the residuals against the fitted values, or against each predictor variable. A correct model specification would give a random scatter of the points; a non-random pattern may indicate mis-specification of the model.

5.3.2.2 Autocorrelation

The least squares regression model assumed that the error terms are uncorrelated random variables or independent normal random variables. In some cases, errors are correlated over time or space when data are collected over time or over space, as is the case with this data. Error terms correlated over time are said to be autocorrelated, or serially correlated. Similarly, error terms correlated over space are spatially correlated. In this data, there is concern that the gyroscope grade data, which were collected over different grade values, may be spatially correlated. The value of any given residual would, therefore, be a function of previous grade values (thus a function of previous readings).
There are two major causes of autocorrelation in time and spatial series data: first is the omission of key variables in the model specification, and second is the presence of systematic coverage errors in the response variable series.

When the error terms are autocorrelated the use of OLS procedures is suspect (Neter et al., 1996) because:

1. The estimated regression coefficients no longer have the minimum variance property and may be inefficient.

2. MSE may seriously underestimate the variance of error terms.

3. OLS procedures may seriously underestimate the true standard deviation of the estimated regression coefficient.

4. Tests using the F and t distributions are no longer strictly applicable.

In this study, the Durbin-Watson test for autocorrelation was used to test for spatial correlation in the grade data. The test assumes the first order autoregressive error model:

\[ Y_t = \beta_0 + \beta_1 X_t + \varepsilon_t \]

\[ \varepsilon_t = \rho \varepsilon_{t-1} + u_t \]

where: \( |\rho| < 1 \) is called the autocorrelation parameter, and

\( u_t \) are independent \( N(0,\sigma^2) \).

From Equation 5.12, the error term at time \( t \) is a function of the error term at time \( t-1 \). In the case of the grade data, this can be interpreted as the error in the grade value at a position \( P_t \) being potentially a function of the error term at the previous position \( P_{t-1} \).
where \( P \) identifies not just the position per se, but the value of the grade at that point. The existence of a first order autoregressive model is detected by an analysis of the residuals from the fitted regression function:

\[
e_t = Y_t - Y_{\text{pred}}
\]

from which the Durbin-Watson test statistic \( D \) is calculated as:

\[
D = \frac{\sum_{t=2}^{n} (e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2}
\]

5.15a

\( D \) is compared to tabulated upper and lower bounds, \( D_U \) and \( D_L \), calculated for various sample sizes at different levels of significance. The decision rules are:

- if \( D > D_L \) conclude \( H_a; \rho = 0 \),
- if \( D < D_U \) conclude \( H_a; \rho > 0 \),
- if \( D_L \leq D \leq D_U \) no decision – the test is inconclusive. 5.15b

Where the test is inconclusive, small values of \( D \) would suggest \( H_a \) while large values would suggest \( H_0 \).
The initial test showed that the grade data were spatially correlated. From the theoretical understanding of the data generating process, an autoregressive model was not unexpected since the vehicle characteristics may be a function of grade. Specifically, the deflection of the vehicle suspension may be a function of grade severity and road surface unevenness. The inclusion of an additional predictor variable (speed) in the model development failed to eliminate the autocorrelation, hence remedial action was taken. This involved a transformation of the variables, utilizing a property of the first-order autoregressive error term regression model of Equation 5.14: specifically, the transformation reduces the error terms to independent disturbance terms (Neter et al., 1996). Given the transformed variables:

\[
Y_t' = Y_t - \rho Y_{t-1}
\]

\[
X_t' = X_t - \rho X_{t-1}
\]

and recalling from Equation 5.14, \( \epsilon_t = \rho \epsilon_{t-1} + u_t \)

it can be shown that:

\[
Y_t' = \beta_0' + \beta_1' X_t' + u_t
\]

where:

\[
\beta_0' = \beta_0(1 - \rho) \\
\beta_1' = \beta_1
\]

Equation 5.17 is a standard simple linear regression with independent error terms \( u_t \), obtained by use of the transformed variables \( Y_t' \) and \( X_t' \). In order to use transformed
model 5.17, \( p \) needs to be estimated. Once this estimate (denoted by \( r \)) is obtained, transformed variables are calculated from it:

\[
Y'_{t} = Y_{t} - rY_{t-1} \\
X'_{t} = X_{t} - rX_{t-1}
\]

Regression model 5.17 is then fitted to the transformed data, yielding the estimated regression function:

\[
Y'_{(p)} = b_0' + b_1'X' 
\]  

5.18

If this eliminates the autocorrelation, it is then transformed back to the original variables:

\[
Y_{(p)} = b_0 + b_1X
\]

using, from 5.17,

\[
b_0 = b_0' / (1 - r) \\
b_1 = b_1'
\]  

5.19

The Cochrane-Orcutt procedure was used to obtain the estimate \( r \) of the autocorrelation parameter. The Cochrane-Orcutt estimation of the autocorrelation parameter is:

\[
r = \frac{\sum_{i=2}^{n} e_{t-1}e_{t}}{\sum_{i=2}^{n} e_{t-1}^2}
\]

5.20

This procedure was used to test for autocorrelation in the first model developed for the full data set. Appendix C shows the calculations of both the Durbin-Watson test statistic
and the Cochrane-Orcutt autocorrelation parameter estimate: the results are described in Section 5.3.3.

5.3.3 Diagnostics and Tests for Model Adequacy

After a model is selected for a data set, it is important to examine the appropriateness of the model. In OLS procedure, this is usually accomplished by examining to see if the initial assumptions of normality, variance equality, and independence of the residuals are satisfied. These properties must be satisfied for the coefficient estimates to be termed BLUE. Several formal and informal tools are available. This analysis first relied upon an informal method, then employed a formal method in questionable cases. The most informative of the informal methods is to look at the model graphically, using plots that, taken together, reveal strengths and weaknesses of the model. Where remedial measures are necessary, the model is modified accordingly. Finally the model that meets these conditions while minimizing the MSE is selected as the calibration model. The tests for model adequacy are now discussed.

5.3.3.1 Test for Normality of Error Terms

Two informal, graphical procedures are available for testing the normality of residuals. The first utilizes a quantile-quantile plot of the residuals; essentially the plot compares the distribution function of the residuals to a hypothetical normal distribution function. If a majority of the ordered residuals cluster along the superimposed hypothetical quantile-quantile line, there is strong evidence that the residuals are nearly normal. The second
graphical method plots the histogram of the residuals, and this is visually examined against the typical bell shape of the normal distribution. A slight departure from normality will not severely compromise the consistency, bias, or efficiency of the estimated parameters (Neter et al., 1996).

5.3.3.2 Test for Constancy of Error Variance

A plot of the residuals against the fitted values provides a means of identifying any patterns in the residuals. If the error variance is constant, this plot will show a random scattering of points around the zero line, since they represent the noise in the data. A second plot used to identify structure in the data is the square root of the absolute residuals against the fitted values; this plot is also useful in identifying outliers in the data. A good model will also show random behavior in this plot.

5.4 Development of the Gyroscope Output Calibration Model

The major goal of this research is to develop a methodology to reliably measure roadway grade in kinematic mode at a spatial resolution suitable for use in GIS-based vehicle emission models. At the core of this effort is the development of the gyroscope calibration model which will essentially convert the raw gyroscope readings to actual roadway grades. Thus, the model is a predictive one and the methodology developed here can be readily adopted to measure road grade elsewhere.
The statistical analysis software package, S-PLUS, was used in developing the models. The S-Plus output for the promising models attempted are enclosed in Appendix C: the output for each model comprises of the following:

- **Summary output** of the regression coefficient estimates with their standard errors and t-values, as well as regression residual standard error, $R^2$ value, F-statistics, and p-value.

- **Residuals vs. Fitted Values plot**: useful for making statement about the model specification and about general trends (correlation) in the data.

- **Square root of absolute residuals against fitted values**: useful for identifying outliers and visualizing structure in the data.

- **Normal quantile plot of residuals**: useful for visually assessing the assumption of normal error distribution.

- **Residual – Fit spread or (r-f) plot**: this plot compares the spread of the fitted values with the spread of the residuals. It is desired that the spread in the fitted values be more than that in the residuals.

- **Cook's distance plot**: gives a measure of the influence of individual observations on the regression coefficients.

These plots provide informal means of testing the model adequacy and assumptions. Formal tests were performed for the final selected models.
5.4.1 Model Specification

The first step in developing a model is to make a decision on whether to use a parametric or non-parametric approach. Parametric methods are useful with data sets which distributions are either known or can be guessed with a certain degree of certainty. In this analysis, simple linear regression with OLS procedures were employed. The underlying assumptions underpinning this parametric method were discussed in Section 5.2.1.

The next step in the process is the selection of model variables. It is important that predictor variables are selected to include all factors that influence the response variable. In this study, the gyroscope output is used as a predictor of the actual road grade; but other factors also affect the gyroscope output itself. These factors do not directly impact the response variable (road grade), rather the effect is on the magnitude of the error in the predictor variable (gyroscope output). Since the effects cannot be controlled or measured, the only obvious predictor for determining the roadway grade remains the gyroscope output. With proper field procedures such as maintaining a steady speed and avoiding sharp accelerations (decelerations), potholes, and bumps, the errors in the gyroscope output will be reduced. With the expressed concern about lagged measurement effect, the data analysis also includes investigation of space dependent correlation in the data. The predictors used to investigate data correlation include vehicle
speed, change in grade, and rate of change in grade in consecutive grade data measurements.

5.4.2 Exploratory Data Analysis

In the first step of developing the calibration model, a scatter plot of the gyroscope output (Reading) was plotted against the actual measured roadway grade in Figure 5-1. This enables a visual examination of the functional form of the relationship between the variables, which can be discerned from the figure as linear. However the linearity does not seem to be equal throughout the data. In particular, Figure 5-1 seems to indicate that the relationship when the grade is positive shows a different slope from that when the grade is negative.

To investigate this further, it was postulated that if the gyroscope responded in a similar way on both positive and negative grade types, then a plot of the output on a section of road when the vehicle is going in one direction would be a mirror image of that when going in the opposite direction. In that case, the grade at the stations would be equal in magnitude but differ only in their signs. This was implemented by plotting the data from the three road sections used to generate the calibration data, namely, the high grade, the medium grade, and the level grade. The grade plots are shown in Figures 5-2 through 5-7. In all three cases, it is evident from the figures that the difference in the actual grade value and the gyroscope reading is consistently higher when the grade is negative than when the grade is positive. In practical terms, the linear relationships for positive and
Figure 5-2:  Error Margin in Gyroscope Data on Positive High Grade

Figure 5-3:  Error Margin in Gyroscope Data on Negative High Grade
Figure 5-4: Error Margin in Gyroscope Data on Positive Medium Grade

Figure 5-5: Error Margin in Gyroscope Data on Negative Medium Grade
Figure 5-6: Error Margin in Gyroscope Data on Positive Level Grade

Figure 5-7: Error Margin in Gyroscope Data on Negative Level Grade
negative grades are different, and this may result from different initial bias (intercept) or
different slope coefficients in the linear relationship.

For the level grade segments there is a general randomness in the data that is similar for
both positive and negative grades. The explanation for this is that on level grades the
gyroscope output is well within the inherent equipment error range (which have been
established to be between +1.296 and −1.35) so that the gyroscope readings in that range
of grade are saturated by the errors. Thus, on level grades where the readings fall around
this range, the instrument output may contain larger relative errors than the rest of the
data.

The difference in the linear relationship between steeper positive and negative grades
may have to do with the vehicle suspensions and how they respond on the two grade
types. When a vehicle is in motion the suspensions will naturally deflect from the
horizontal, level position. It appears that in the test vehicle, the suspensions deflect more
when the vehicle is going up grade than when it is going down grade. This is somewhat
counter-intuitive because with the weight of the vehicle engine pressing forward, it would
be expected for the suspensions to deflect more on a downgrade. But without
undertaking a detailed calibration of the suspensions the exact amount of deflection
cannot be determined.
From the discussion above it is apparent that the sign of the road grade (positive vs. negative) is an important factor in modeling the gyroscope output. This is indeed the case as the final calibration model developed in Section 5.4.4 utilizes an indicator variable to discriminate between positive and negative grades.

5.4.3 Model Development with the Full Data

The entire calibration data set contains 288 grade measurements with several repeated measurements for each grade value. It is desirable that a single model be developed that will adequately fit the entire data, with the underlying requirement of minimizing MSE. Thus the model building exercise was started with a simple linear model that was fit to the full data; this is labeled as Model-C1 in Appendix C. The diagnostic plots from S-Plus are shown as Figure C1-a through Figure C1-f, while the summary output from Appendix C is reproduced below as Table 5-1. The model itself is stated at the bottom of the table.

An inspection of the output shows the multiple $R^2$ for this model is 97.81, usually considered good. The very high t-values on the estimates and F-statistics of the regression also indicates a high goodness of fit. However the MSE of 1.124 is rather high (compared to other models developed subsequently). Recall from the discussion in Section 5.2.1 that a combination of low MSE, high multiple $R^2$, and high F-statistics indicates a good model fit. More importantly, an examination of the residuals plot, reproduced below as Figure 5-8, reveals a definite trend in the data as the points are not
Table 5-1: Summary Statistics: Simple Linear Model with Full Data

Model 1: Full Data Model (linear, non-transformed variables)

> summary(ugrd.lm)

Call: lm(formula = Grade ~ Reading, data = ugrdata)
Residuals:
  Min     1Q Median     3Q    Max
-2.85 -0.8351 0.001046 0.8049 3.009

Coefficients:
            Value Std. Error t value Pr(>|t|)
(Intercept) -0.7779   0.0666  -11.6782    0.0000
  Reading    1.5393   0.0136   113.1110    0.0000

Residual standard error: 1.124 on 286 degrees of freedom
Multiple R-Squared: 0.9781
F-statistic: 12790 on 1 and 286 degrees of freedom,
the p-value is 0

Correlation of Coefficients:
   (Intercept)  
Reading -0.1032

Model-C1 is:

\[
\text{Grade} = -0.7779 + 1.5393 \times \text{Reading}
\]
Figure 5-8: Residuals vs. Fitted Values: Linear Model with Full Data
randomly scattered. This could indicate that the data is spatially correlated, or that the model specification is wrong. The residuals show a general trend of negative values at high positive and negative grades, and fairly well distributed residuals between.

The Cook’s distance plot shows data points that could be outliers. An outlier is a data point that is statistically outside the normal range of the data at that level. OLS procedure is very sensitive to outliers because of the significant influence they have on the normality and constancy of residuals. In normal practice, outliers are discarded if found to be obvious mistakes, or clearly belong in a different data category. But, in this analysis a deliberate effort was made to preserve all possible data effects in the model; as a result no data points were eliminated. All the data points are integral parts of the equipment output, and are not necessarily mistakes. Therefore analysis of the Cook’s distance plot was not put to much use beyond helping to identify possible data influences that could explain non-normality in the error distribution.

To formally test if the data are correlated, the Durbin-Watson test was employed (the calculation steps are given in Section C.1 of Appendix C). The Durbin-Watson test statistic from that calculation was given as:

\[ D = 0.58 < D_L = 1.65, \text{ conclude } H_0: \rho > 0 \]

By concluding that the correlation parameter \( \rho \) is greater than zero, the test formally confirms that spatial correlation exists in the data. As stated earlier, autocorrelation in
data may indicate the absence of a relevant predictor variable in the model specification that can help explain and thus eliminate the trend. The only other available measurable (and recorded) quantity in the data set that could possibly explain this trend is the vehicle speed. It was reasoned that the reaction of the vehicle suspension may actually be sensitive to the vehicle speed, and so can help explain the trend noted in the data. Thus the vehicle speed was offered as an additional predictor in a new model (Model-C2). The results, as seen in the summary Table C2-a, did not significantly improve the model. The multiple $R^2$ and residual standard errors remained identical. More importantly the very high $p$ value for the speed variable suggests that speed is a poor explanatory variable in the model. Even the inclusion of indicator variables for the grade signs (positive or negative) was also unsuccessful at improving the model.

The next step was taken to transform the model variables to see if the correlation could be eliminated. The Cochrane-Orcutt procedure was used to calculate an estimate $r$ of the autocorrelation parameter $\rho$ to be:

$$r = 0.283$$

(See Section C.2 in Appendix C for the detailed calculations)

The summary output of the model using the transformed variables is shown as Table C3-a, and the diagnostic plots are given in Figure C3-a through Figure C3-f. As can be seen from the residual plots, the transformed variable model shows some improvement in randomizing the error terms, but the trend was still present. A formal determination with
the Durbin-Watson test statistic confirmed this. However, the transformation was accompanied by a reduction in the residual mean error to 1.072 while the multiple R² value remained high at 96.76%. The estimated parameters from the transformed model were then transformed back to the original variables and another model was developed. The fitted values of the resulting model, however, showed considerably large prediction errors (some as large as 3.6%), especially for both positive and negative high grades. This level of prediction error was deemed unacceptable for measurement of grade for use in air quality analysis, so this model was not pursued further. A prediction error of 0.5%, or as near this value as possible, is desired.

Since the model prediction errors are much larger at the extreme high grades, and recognizing that on most roadways grades steeper than 7.0% are rare, a decision was made to reduce the model scope to ±10.5%. In as much as this limit is as arbitrary as the original ±14.6% that was started with, there is a practical reason for selecting it. During the data collection exercise, the grade data higher than ±10.5 were collected on the same high grade road segment. It follows, therefore, that in reducing the model scope, a good limit would be one that eliminates the data points collected on that road segment. This will eliminate any interaction effects that may be introduced by retaining some of the high grade data. With the model scope reduced, the trimmed data is now used for the calibration exercise. The trimmed data contains a total of 228 data points comprising grade measurements in the range of +10.5% to −10.5%, with corresponding gyroscope readings in the range of 7.65 to 6.235, respectively.
5.4.4 Model Development with the Trimmed Data

The first attempted model with the trimmed data was a simple linear model using the gyroscope reading as the only predictor variable. Similar to the simple model developed with the full data set, it was not unexpected that this model would also exhibit some spatial correlation. This was the case as shown by the diagnostic plots for the model in Figure C4-a through Figure C4-f in Appendix C. The residuals plot in Figure C4-a shows that the trend is still there. A transformation of the data with the Cochrane-Orcutt procedure also presented similarly large prediction error problems as discussed for the full data model.

Several trial models (more than 20) utilizing additional explanatory variables, or different transformations of the variables were tested, but most were adjudged unsatisfactory. Some of the tested models use explanatory variables that include lagged measurement effects and polynomial transformations. These models have not been documented here for the sake of brevity and clarity of presentation. On a comparative basis the two models that gave significantly good results (in terms of minimizing the residual standard error and the prediction errors, and significantly eliminating the spatial correlation in the data) are shown as Model C5 and Model C6 in Appendix C.

Model C5 has the gyroscope readings and the magnitude of the change in the readings between consecutive points as predictor variables. The change in the magnitude of the gyroscope readings was utilized as a variable to capture the lagged measurement
dependence discussed in Section 5.3.2. The summary output of Model C5 is shown below as Table 5-2, with the model given at the bottom of the table. The grade vs. fitted values and residuals vs. fitted values plots are shown as Figure 5-9 and Figure 5-10, respectively. The regression line appears to fit the data set reasonably well, with high model F statistics and low p values for the parameter estimates.

The inclusion of the change in reading parameter could be useful in reducing the spatial correlation in the data. At the rate that the grade data was collected, it was reasonable to expect that adjacent points would have grades with similar magnitude and sign. This may have created the trend observed in the errors. A formal test for error correlation in this model with the Durbin-Watson test statistic gives:

$$D_L = 1.63 \quad < \quad D = 1.67 \quad > \quad D_U = 1.72$$

Therefore the test was inconclusive.

Though the model showed a reduction in the residual standard error to 0.8334 and a slight increase in the multiple $R^2$ value to 97.5, the important aim of eliminating the error correlation was still not achieved.
Table 5-2: Summary Output for Trimmed Data Model (Reading + Change in Reading as Predictor Variables)

```r
> summary(rcgrd.lm)

Call: lm(formula = Grade ~ Reading + Creading, data=aldata)
Residuals:
   Min     1Q   Median     3Q    Max
-2.308 -0.546  0.002793  0.5737  2.271

Coefficients:
            Value Std. Error t value Pr(>|t|)
(Intercept) -0.6986   0.0558  -12.5158  0.0000
Reading     1.5789   0.0169   93.5969  0.0000
Creading   -0.7583   0.0656  -11.5585  0.0000

Residual standard error: 0.8334 on 225 degrees of freedom
Multiple R-Squared: 0.975
F-statistic: 4380 on 2 and 225 degrees of freedom,
The p-value is 0

Correlation of Coefficients:
 (Intercept)  Reading
Reading  -0.1335

> The Model is:

\[
\text{Grade} = -0.6986 + 1.5789 \times \text{Reading} - 0.7583 \times \text{Creading}
\]
Figure 5-9: Grade vs. Fitted Values: Trimmed Data (Reading + CReading)

Figure 5-10: Residuals vs. Fitted Values: Trimmed Data (Reading + CReading)
In Model C6, an indicator variable representing the sign of the readings was utilized with the gyroscope reading as main effect variables. Recall from Section 5.4.2 that the exploratory data analysis had indicated a difference in the gyroscope reading for positive and negative grades. The use of an indicator variable for the output sign effectively fits a piece-wise model for positive and negative grades that is continuous throughout the data. By so doing the distribution of the errors is better randomized.

Table 5-3 shows the summary output of Model C6. The grade vs. fitted values and residuals vs. fitted values plots are shown as Figure 5-11 and Figure 5-12, respectively. The regression line also appears to fit the data set reasonably well, with high model F statistics and low p values for the parameter estimates. But these values are not as good as in Model C5. The Durbin-Watson statistic for this model gives:

$$D_L = 1.63 \ < \ D = 1.70 \ > \ D_U = 1.72$$

Therefore the test here was also inconclusive.

However, the residuals here appear to be more randomly distributed and closer to normal than for Model C5. The value of the test statistic is only marginally less than the upper bounds for acceptance.

More importantly, the model validation results, discussed in Section 5.4.5 below, showed that almost all of the point prediction errors fall within 1.0% of the actual grade value. When combined with its other good statistics, such as low prediction error, this model was accepted as the “best” model, and was therefore selected as the calibration model.
Table 5-3: Summary Output for Trimmed Data Model (Reading + Sign of Reading as Predictor Variables)

> summary (grdmod)

Call: lm(formula = Grade ~ Reading + Signvar, data= grddrd)
Residuals:

          Min       1Q   Median       3Q      Max
-2.153 -0.7171 -0.01953  0.6993  2.75

Coefficients:

             Value  Std. Error t value  Pr(>|t|)
(Intercept) -0.4950  0.1298    -3.8124   0.0002
Reading      1.5954  0.0359     44.4412   0.0000
Signvar    -0.3256  0.2367    -1.3756   0.1703

Residual standard error: 1.048 on 225 degrees of freedom
Multiple R-Squared: 0.9604
F-statistic: 2730 on 2 and 225 degrees of freedom, the p-value is 0

Correlation of Coefficients:

     (Intercept) Reading Signvar
Reading    0.6430
Signvar   -0.8426  -0.8100

> The Model is:

Grade = -0.4950 + 1.5954*Reading - 0.3256*Signvar
Figure 5-11: Grade vs. Fitted Values: Trimmed Data (Reading + Signvar)

Figure 5-12: Residuals vs. Fitted Values: Trimmed Data (Reading + Signvar)
Model C6 is formally stated as:

\[
\text{Grade} = -0.4950 + 1.5954 \times \text{Reading} - 0.3256 \times \text{Signvar} \quad (5.21)
\]

where:  \( \text{Reading} = \) gyroscope output, and

\[
\text{Signvar} \text{ (the indicator variable)} = \begin{cases} 
1, & \text{if Reading} > 0 \\
0, & \text{if Reading} \leq 0
\end{cases}
\]

Having decided on the model, the next step was to test the validity of the initial assumptions about the error terms in order for the use of OLS procedures to be valid. Finally, a test for the model adequacy through a validation procedure completed the process.

5.4.4.1 Test for Normality of Error Terms

The quantile-quantile plot of Model C6 is shown as Figure C6-d in Appendix C. The figure shows fairly good symmetry, with most of the ordered residuals clustered along the super-imposed quantile-quantile line. The flared values at the extremes can be attributed to outlying data that we had chosen not to filter. Also, recall that normality is usually difficult to establish conclusively because a wrong model specification or non-constancy of error variance may induce departures from normality (Neter et al., 1996). But when combined with the other properties of the model, the quantile-quantile plot gives
indication that the errors are normal. It can therefore be concluded that the normality of error terms criteria has not been violated.

5.4.4.2 Test for Constancy of Error Variance
A visual examination of the residuals plot in Figures 5-12 indicates there may still be some correlation in the data, but as stated earlier, a formal test with the Durbin-Watson procedure was inclusive. Recall that in such inconclusive cases, high values of the Durbin-Watson statistic suggests no correlation, as explained in Sub-section 5.3.2.2. The value of 1.70 calculated for the statistic was very close to the 1.72 upper bounds for a conclusion of no correlation. Also, the square root of the absolute residuals versus the fitted values plot in Figure C6-b shows no obvious trend in the data. It can be said that what correlation there is in the data is not severe, and it can be concluded that the constancy of error variance criterion was not seriously violated.

5.4.5 Validation of the Selected Calibration Model
The final step in the model development is to validate the model results. This exercise evaluates the predictive ability of the model by comparing grade values predicted from the model to actual measured grade values. A regression model developed from a given data largely implies that the model fits well the data in hand. For a different set of random data, the model could very well have been different. As a result, the error mean square MSE will tend to underestimate the inherent variability in making future predictions (Neter et al., 1996. One measure of a model’s actual predictive ability
involves using the model to predict grade values in a new data set, and then calculating
the mean of the squared prediction errors - or the *mean squared prediction error* (MSPR).
The MSPR is given as (Neter et al., 1996):

\[
MSPR = \frac{\sum_{i=1}^{n^*} (Y_i - Y_{(p)i})^2}{n^*}
\]

where:

- \( Y_i \) = the grade value in the \( i \)th validation case
- \( Y_{(p)i} \) = the predicted grade value for the \( i \)th validation case based on the
  model building data set
- \( n^* \) = the number of cases in the validation data set

If the MSPR is fairly close to MSE calculated with the model-building data set (in this
case, the calibration data), then MSE is not seriously biased, and it gives an appropriate
indication of the predictive ability of the model. If MSPR is much larger than MSE, then
it should be used as an indicator of the model prediction ability (Neter et al., 1996).

Another goal of the validation exercise is to define a measure of confidence in the
predictions given by the model. To do this, the standard deviation of the prediction errors
from the validation exercise was calculated. It follows that about 68.27% of the predicted
values will fall within one standard deviation of the true grade value, and about 95.45%
will fall within two standard deviations.
Two sets of data were used in the model validation exercise. The data were collected independently from roads other than the ones from which the calibration data were collected. The roads were driven only once with no repeated measurements. Thus, in the evaluation tables that are presented subsequently, equal grade values actually refer to different stations of equal grade rather than repeated measurement at the same station. The model was applied to the validation data and the results are shown in Table C7-a and in Table C7-b.

Table C7-a shows that most of the point prediction errors fall under 1.0% grade of the actual grade value. The MSPR was calculated to be -0.26; but recall that the residual standard error for this model was 1.048. Therefore, the standard error will serve better as an indicator of the predictive ability of the model. The predicted grades were plotted alongside the measured grade in Figure 5-13 below. The figure shows there are relatively small deviations from the measured grade.

The standard deviation of the prediction errors was calculated to be 0.53. This means that at least 68% of the predicted grade values falls within one standard deviation (0.53% grade) of the measured grade value, and 95% falls within two standard deviations (1.06% grade) of the measured grade. A histogram of the prediction errors is shown as Figure 5-14, indicating the near normal distribution of the prediction errors. It was previously
Figure 5-13: Model Validation I: Comparison of Measured and Model-Predicted Grade

Comparison of Measured and Predicted Grade

- Measured Grade
- Predicted Grade

Station

Grade (%)
Figure 5-14: Histogram of Model Prediction Error Distribution
stated that it was desired for most of the prediction errors to fall within 0.5 of the predicted grade. This was achieved with at least 68% of the validation data.

The model prediction for the second road in Table C7-b is not as good as for the first road, but the results are comparable. In this case, the standard deviation of the prediction errors is 0.66, which indicates that about 68.0% of the predicted grades fall within 0.66% grade of the actual grade, while about 95.0% fall within 1.36% grade of the actual grade. The MSRP was calculated to be 0.53 which, as in the first case, is also lower than the residual standard error of the model. With these two sets of independent data, the predictive validity of the model has been established. There is room for improvement in the methodologies, but better equipment is needed.

Having completed the process of model development and validation, the next task is the documentation of the practical field procedure for the utilization of the methodology developed in this research. This is taken up in Chapter VI.
CHAPTER VI

PROCEDURE FOR FIELD IMPLEMENTATION OF PROCEDURE

This chapter describes the step-by-step implementation of the methodology developed in this research. Two different field procedures are stipulated; one is for collecting the gyroscope calibration data, and the other is for acquisition of spatially resolved roadway grade. The difference arises because different software programs are used in either case. The system calibration data need be collected only once. However, every vehicle to be used for grade data collection must have a different set of calibration data (collected with the vehicle) to develop the appropriate calibration models. In doing so the GPS unit is not needed, so a data logging computer with a single serial port to connect the gyroscope to is sufficient. On the other hand, collecting data for spatially resolved road grade requires a computer with dual serial ports for connecting both the gyroscope and the GPS receiver. The procedure for collecting either type of data involves three component operations, namely: equipment connections, data collection, and data processing and analysis.

It is recommended that the sequence for implementing the procedures be to first collect and complete the analysis of the calibration data before collecting the spatially resolved grade data. That way the operator is sure that an appropriate calibration model is
available before embarking on large scale grade data collection. However, in putting this section together, the presentation would be clearer if the procedures for the acquisition of the spatially resolved grade data is presented first. This is because the grade data collection procedures incorporate most of the steps that are repeated when collecting calibration data.

6.1 Procedure for Collecting Spatially Resolved Roadway Grade Data

The process for collecting the spatially referenced grade data involves two data collecting activities: (1) collecting the spatially resolved roadway grade data, and (2) collecting the GPS base station data. The GPS base station data is used to post-process the GPS spatial data collected with the grade data.

6.1.1 Procedure for Logging GPS Base Station Data

The GPS base station used in this research is located on top of the Mason Civil Engineering Building at the Georgia Institute of Technology. It is an Ashtech Z-12 receiver and is operated with the Ashtech PRISM software. Before going out for roadway grade data collection, the GPS base station must be turned on. This is the procedure for logging the base station data:

1. Click on the PRISM icon on the desktop to open the program.
2. Select the correct communication port on the computer (COM 1) to which the receiver is connected.
3. Select the {baud rate} for data logging. A baud rate of 38400 was normally used in this research.

4. Give a full path name to the folder where the data file is to be stored.

5. Tab to the {B-filename} box and give a filename. It is recommended that only the first four characters in the filename be changed; the other characters should be left as is. For proper data file identification, the date (month and day) of the file’s creation is used. For example, a base station file logged on June 16 will have 0616 as the beginning four characters.

6. Use the right arrow to move to the {C-filename} box. Both the C-file and the E-file automatically take the same name stipulated for the B-file but with a C and E. respectively, at the beginning.

7. Press [F10] to start logging data.

The setting on the receiver is for a data logging interval of 1 second. At the end of the data logging, to exit from PRISM, do the following:

8. Press [Escape]

9. Confirm the exit command by pressing [Y]. The data file is automatically saved on exit.

6.1.2 Equipment Connections for Grade Data Collection

The equipment for this exercise are the DMU-FOG, the Workhorse GPS receiver, and the data logging (Data Brick) computer. The DMU-FOG is fixed on a platform made out of
a plastic box with four holes drilled at the top for attaching the gyroscope. The platform is centered as close as possible between the four wheels of the vehicle. This will correspond to the center of rotation of the vehicle chassis. This is important in helping to ensure that the gyroscope responds only to true changes in road alignment rather than plane rotation of the chassis.

1. Attach the DMU-FOG to its platform by screwing it on tightly with four screws. With the vehicle on a near zero grade, use a carpenter level to ensure that the gyroscope platform is level; if it is not, gently release the appropriate screws to achieve a balance, while still making sure that all the screws are still tight.

2. Connect the DMU-FOG to the data brick computer. Connect the 15 pin end of the connection cable to the gyroscope and the 9-pin end to serial port 1 (COM 1) of the computer.

3. Connect the DMU-FOG to its power source. The power cable is the additional black and red wire on the connection cable. Match the red wire to the (+) positive terminal and the black wire to the (-) ground terminal of the battery. **DO NOT REVERSE THE POWER LEADS.** The power supply to the DMU-FOG should be 14 – 30 Volts DC at 1 Amp. Once the power is connected the unit is on; there is no ON / OFF switch.

4. Connect the antenna of the Workhorse GPS to the receiver unit, and place the antenna on the vehicle roof (preferably in the middle of the roof, and directly over
the gyroscope platform). The antenna has a magnetic base and should attach readily to the metal of the roof top.

5. Connect the GPS receiver to the data brick computer. Connect the OSX snap on end of the connection cable to the GPS receiver and the 10-pin end to serial port 2 (com port 2) of the computer.

6. Connect the GPS receiver to its power source. There is a separate power cable for the GPS unit. Match the red wire to the (+) terminal and the black wire to the (-) terminal of the battery. DO NOT REVERSE THE POWER LEADS. The power supply should be 5 Volts at 230 mili-Amps.

7. Turn on the GPS unit with the ON/OFF switch; a flickering red light gives indication that the unit is on and working properly.

8. Connect the inverter / adapter cable to the cigarette lighter hole of the vehicle. Then connect the data brick computer to the inverter.

9. Start the vehicle engine and switch on the ON / OFF switch of the inverter.

10. Now, turn on the data brick computer with its ON / OFF switch. The computer will boot for a few seconds before coming on.

IMPORTANT:

- Reversing the battery leads will damage the equipment; so care must be taken when making the power connections.

- Connect both the DMU-FOG and the GPS units to the data brick computer, and have both running before switching on the computer. If the computer is switched on
before both units are connected, the computer will not recognize or receive the signals.

- On this particular data brick computer, serial port 2 is where the mouse used to be connected. But it had to be disabled in order to use that port for the GPS connection. As a result, on-screen navigation is possible only through the keyboard. Thus, the instructions given here follow the keyboard operations. The task of controlling and running the VIs will be easier with a computer that has dual serial ports and an internal mouse. In that case, using the mouse will replace the keyboard operations.

- It takes a few minutes to get all the units connected. To save on battery power, it is preferred that all the connections be completed before the units are turned on. After all the units are connected, do the following:
  - Connect the DMU-FOG power cable; this automatically turns the unit on.
  - Connect the GPS power cable and switch on its ON / OFF switch.
  - Finally, turn on the data brick computer by switching on its ON / OFF switch.

6.1.3 Zeroing the Gyroscope

Prior to taking grade readings, the gyroscope needs to be zeroed. The DMU-FOG calculates an angle (pitch and roll) by integrating the output of the angular rate sensors. Rate sensors are subject to small offsets in the angular rate measurement. A constant offset error in angular rate will get integrated into an error in angle that increases with time; this is called angular drift. The zeroing operation measures the initial bias in the angular rate sensors, and restores them to initial state, thus eliminating the drift. It is
recommended that the gyroscope be zeroed at least every three hours of continuous operation. It should be zeroed more frequently if subjected to large shocks or extreme temperatures. In this research the recommended interval of three hours was adopted, and this seemed to work well.

The zeroing operation is done with X-View software with the vehicle standing still. The X-View program is also used for collecting calibration data, so a more extensive discussion of its configuration is given in Section 6.2. It is assumed here that the X-View setup and configuration has been completed, so all that needs to be done is to zero the gyroscope.

1. Press [Control]+[Escape]: this will activate the [Start] icon in Windows.
2. Use arrows to move to [Programs]
3. Press [Enter]: this will bring up a list of programs in Windows.
4. Use arrows to move to [Crossbow] → [X-View]
5. Press [Enter]: this will open the X-View program
6. Use [Arrow] and [Tab] keys to go to [Graph]
7. Press [Enter]: this will bring up the roll / pitch graph. On this screen is also the zeroing icon.
8. With the vehicle standing still, tab to the zero icon and press [Enter]. The zeroing operation takes a few seconds to complete.
9. Now, exit from X-View: Tab to the [Close] icon and press [Enter]; then tab to the [Exit] icon and press [Enter].
This completes the zeroing operation. The gyroscope need not be level during the zeroing operation, but it should be still. With no motion (zero angular rate), the zeroing operation measures the bias in the output of the angular rate sensors.

6.1.4 Data Collection

After all the units are connected and running, and the gyroscope has been zeroed, the system is ready to take grade readings. This is done with the LabVIEW Virtual Instrument (VI) programs, as described in Chapter Four. The procedures are as follows:

1. Press [Control]+[Escape] to activate the {Start} icon in Windows.
2. Use arrows to move to {Programs}.
3. Press [Enter] to bring up a list of programs in Windows.
4. Use arrows to move to {Gps-Gyro}.
5. Press [Enter]: this will open the LabVIEW virtual instrument programs.

Four LabVIEW VI programs are opened; they are:

(i) Log WHII.vi: This VI collects GPS data from serial port 1, and stores them in a Motorola binary file (.pdr) format. The file so created contains the spatial data for locating the grade data. The Motorola binary file format is used because the post processing software is based on this file format.
(ii) WH position-status.vi: This VI gives a text-based and readable screen display of the GPS data. It does not log to a file, rather it allows the operator to see, in real time, the status of the GPS signals.

(iii) DMU Example.vi: This VI logs the gyroscope road grade data from serial port 2. It does not log to a file, but it gives a screen display of the real time status of the grade data.

(iv) Gps-gyro-combo.vi: This is the main control VI that interfaces with the other three VIs. Specifically, it reads in GPS time data from the Log WHII.vi and tags this information to the grade data from the DMU Example.vi. The GPS time-tagged grade data is then written to a text (.txt) file.

The VIs produce two files – a GPS time-tagged text file for the grade data, and a Motorola binary file for the spatial data. The screen that opens on the top when the Gps-Gyro program is opened is the Gps-gyro-combo.vi control screen. The other VIs are open in the background and can be brought forward by pressing [Alt]+[Tab] to highlight the one that is wanted in front. The icon which simultaneously starts all four VIs is on the Gps-gyro-combo.vi control screen. But before running the programs, the following steps need to be completed on the screen:

6. Give a full path name to the folder (directory) where the log file is to be stored. and give a file name with extension (.txt). For example:
C:\gps-gyro\data\I85N.txt (this will log the file I85N.txt to the data folder)

7. Tab to select the correct com port (COM 2).

8. Tab to highlight the {Log Data} switch (which should be in the “OFF” position, indicating that no data is being logged).

9. Start running all four VIs by either pressing [Control]+[R], or go to the drop-down menu and select {Operate} → {Run}.

10. With the {Log Data} switch still highlighted, now start logging grade and spatial data by pressing [Enter]. The {Log Data} switch should now be in the “ON” position, indicating that data is being logged.

Now, drive the vehicle through the selected route, maintaining a constant speed as much as possible. The speed you drive at determines the interval between each recorded position. Though the gyroscope is set to record at 10 Hz, examination of numerous grade data files had shown that the actual number of recorded grade data for each GPS epoch (set at one second interval) averages around six. At 6.0 Hz output rate, and driving at a speed of 40 mph, in theory the average interval between recorded points will be about 10.0 ft; and at 50 mph it will be 12.0 ft. As stated previously, the status of both the GPS and grade data logging can be monitored by pressing [Alt]+[Tab] to highlight and bring forward any of the screens.
11. To pause the data logging, tab to highlight the {Log Data} switch and press [Enter] to turn it to "OFF". This is useful, for example, if the vehicle comes to a stop. To resume, simply press [Enter] to turn the {Log Data} switch to "ON".

At the end of the route, to exit from the VIs and save the data file, do the following:

12. Return to Gps-gyro-combo.vi screen and tab to highlight the {Log Data} switch.
13. Press [Enter] to stop data logging.
14. Tab to the {Close} icon and press [Enter] to close and save the data file.

IMPORTANT:

It is crucial that the data file is closed before the VIs are stopped, otherwise the data files will be lost.

15. Now, exit from the VIs by either pressing [Control]+[Q], or go to the drop-down menu and select {File} → {Exit}. Confirm the exit command and all four VI windows will close.

6.1.5 Data Processing

The next step is to process the two data files to obtain a spatially referenced grade file that integrates information from both files. This exercise involves two operations: post-processing the GPS spatial data, and integrating (or matching) the grade and GPS data.
The GPS post processing exercise is carried out with proprietary software, while the matching of grade and spatial data is carried out by a program written in PERL for that purpose.

6.1.5.1 Post Processing the GPS Data

The base receiver and the rover receiver are from different manufacturers and use different proprietary software. To effect the post processing, both the base file and the rover file must be in the same file format. To do this, the base file is first converted to the Receiver Independent Exchange (RINEX) format, then the RINEX file is converted to the Motorola binary format, the same as the rover file. With both files in the same format, the post processing is then effected. Most manufacturers have utilities for converting from their proprietary format to the RINEX format, and vice versa.

The conversion of the base file to RINEX format is done with the Ashtech PRISM software. The procedure for doing this is detailed in the PRISM Users Manual. The actual post processing of the rover file is done with the Motorola PostPoint software, using the converted base file. The procedure for doing this is detailed in the PostPoint Users Manual. The final output is a corrected GPS data file that is then used for integrating with the grade data file.
6.1.5.2 Integrating the GPS and Grade Data

A program written in the PERL language is used to automate this exercise. The program consists of five sub-programs as described in Chapter IV. The codes are included in Appendix B. For convenience the sub-programs are restated here:

(i) Clean-gps.pl: this formats the post-processed GPS data so that it can be used to match the cleaned gyroscope grade data.

(ii) Clean-gyro.pl: this screens the gyroscope grade data to eliminate values outside the model scope, and formats it for matching with the GPS data.

(iii) Match-gps.pl: this locates the coordinates of each grade data point by matching it with the GPS data and interpolating in between.

(iv) Models.pl: this applies the calibration model to convert each raw gyroscope reading to a percentage grade value; and

(v) Batch.pl: this manages the other three programs.

The programs are run from the DOS prompt, and to do so the appropriate GPS spatial data file and the gyroscope grade file must reside in the same folder as these programs.

At the DOS and in the appropriate folder where the files a located, type:

```perl
> perl batch.pl gps-file gyro-file matched.txt
```

where: gps-file is the name of the appropriate GPS spatial data file,

    gyro-file is the name of the appropriate grade data file, and
matched.txt is the name of the spatially-referenced grade output file. The output file will be in the same final format as that of Table 4-6. To view the data, the file can be imported and displayed in a GIS environment such as TRANSCAD.

6.2 Procedure for Collecting System Calibration Data

The needed equipment are the gyroscope and the data logging computer. The GPS receiver is not needed for collecting gyroscope calibrating data.

6.2.1 Equipment Connections

Follow the instructions in Section 6.1.1 to connect the gyroscope to the data logging computer. The GPS receiver is not needed for calibration data collection.

6.2.2 Data Collection

The calibration data collection is done with the X-View software; this is a proprietary software from Crossbow Technology, Inc. that was shipped with the gyroscope. The software is used because it has a utility that allows the operator to insert markers in the data stream. This makes it possible to identify grade data at selected points that can then be compared with actual measured grade at these points. To collect the calibration data, first select a section of road that includes the grade interval that is to be modeled. Set out station markers along the road section and measure the grade at these points. Start X-View as follows:
1. Press [Control]+[Escape] to activate the {Start} icon in Windows.

2. Use arrows to move to {Programs}

3. Press [Enter]: this will bring forth a list of programs in Windows.

4. Use arrows to move to {Crossbow} → {X-View}

5. Press [Enter]: this will open the X-View program.

6. Correct the {interface} to read the right communication port (COM 2). Check the {status} indicator; if the connection is correct this will read “connected”, if not, check the connection, the power, or the com port assignment.

7. Use the tab key to go to the {Config} icon and press [Enter]; the first configuration screen appears. With the appropriate profile name highlighted in {configuration}, select the {family} name “DMU” and the {product} name “DMU-FOG”. Check that the com port connection (COM 2) and the baud rate are correct (baud rate of 38400 was used in this research).

8. Tab to [Continue] and press [Enter]; this brings up the second configuration screen. Give a full path name to the {folder} where the log file is to be stored, and give a {file name prefix}. X-View has a file naming convention that uses the date and time of the file’s creation. The file name prefix is an optional string attached at the beginning of the file name to help the user identify the data files. For example, the file name prefix “statestreet” for a data file created at 2:55pm on June 16, 2000 will have the file name:

“statestreet-2000-0616-1455.txt”
9. Specify the \{data logging rate\}: this is the period, in seconds, between each data point. Selecting zero will log every data point to file. This option was used for the calibration data for this research, so as to get near instantaneous readings at the position markers.

10. Check that the \{G range\} and the \{angle range\} are correct. An angle range of 45 and G range of 2 were used.

11. Specify the \{integration time\} and the \{zero averaging time\}. Integration time of 5, and zero averaging time of 100 were used.

12. Select the graph type to see an on-screen graphical display of the data. Select the roll / pitch graph type.

13. Tab to \{Change\} and press [Enter]; the settings are saved and the screen returns to the main X-View page.

14. Tab to \{Graph\} and press [Enter] to see the roll / pitch graph; this screen also contains icons to \{Zero\} the gyroscope, \{Start\} data logging, and for inserting \{Mark\} in the data stream.

15. Tab to the \{Zero\} icon and press [Enter] to zero the angular rate sensors. The zero operation takes a few seconds to complete; in any case, wait until the pitch and roll readings stabilize before starting to log data.

16. To start logging data, tab to \{Start\} and press [Enter].

17. Now start driving the vehicle along the road section, maintaining, as much as possible, a constant speed.

\* See the DMU Users Manual for a description of the meaning of these settings.
18. Tab to the {Mark} icon; as the vehicle passes by the station markers established on the ground, press [Enter] to insert a marker in the data stream. The marker will identify the gyroscope output at that point. The markers are numbered from one upwards, and can therefore be related to the station markers on the ground for identification.

19. After the last marker, close the file and stop X-View as follows:

20. Tab to {Stop} and press [Enter]; the main X-View screen comes up.

21. Tab to {Exit} and press [Enter] to exit from X-View.

Repeat this procedure to collect a calibration data set that is large enough and is representative of the range of grade values to be modeled. In this research 288 data points were taken, representing grade values from -14.6% to +14.6%. Designing the procedures for collecting the calibration data is crucial because non-representative calibration data will ultimately result in a wrong calibration model.

6.2.3 Data Processing

The DMU-FOG output file has 13 fields (see Table 4-3), but the ones that are important for the purposes of determining the road grade are the Pitch (field 3) and the Marker (field 13). After collecting the calibration data, the files are opened and the pitch reading at every marker point is copied to a separate file along with the value of the corresponding actual measured grade at the stations. This is the calibration data, and
once created, the measured grade can then be statistically modeled as a function of the pitch reading. The result is a calibration model that can be used to model other grade readings taken with that particular vehicle, using the procedures outlined in Section 6.2. Development of the calibration model was the subject of Chapter V.

6.3 Development of Grade Database for Selected Atlanta Region Roads

As the final objective of the research goal, the methodology developed in this research was utilized to develop a GIS database of grade data for selected roads in the Atlanta region. The selected roads are:

- Both directions of Interstate 85 from Exit 13 (Jonesboro Road) to Exit 43 (Old Peachtree Road).
- Both directions of Interstate 75 from Exit 75 (Stockbridge Road) to Exit 114 (Canton Road).
- Both directions of the loop Interstate 285.

The database was imported and displayed in TRANSCAD, shown in Figure 6-1 below.
Figure 6-1: Map of Grade Data for Selected Atlanta Region Roads
CHAPTER VII

CONCLUSIONS

The major goal of this research was to develop a methodology capable of measuring spatially referenced roadway grade data in kinematic mode. It was important that the methodology be cost-effective, consistent, and repeatable so that it could be adopted by state and local planning and air quality management agencies. To incorporate grade correction factors into vehicle emission modeling, these agencies would be required to map the road grades in their jurisdictions. The research goal and objectives were achieved and, in doing so, this research has made a significant contribution by adding to the tools available for a more accurate accounting of real world conditions in vehicle emission models.

This chapter reviews the major contributions of this research to the extent that the research objectives were accomplished, i.e. a methodology was developed that can measure spatially-referenced road grade in kinematic mode. A discussion of the theoretical and practical limitations of the methodology is presented. And the chapter ends with recommendations for the direction of future research efforts and a general comment on the methodology.
7.1 Major Contributions

The major contribution of this research is that it provides a means of utilizing the attributes of two technologies to complement each other in a manner that solves a major problem in the practice of vehicle emission modeling. The development of grade factors in vehicle emission models is recognized as a major step towards making the modeling process more representative of real world conditions (EPA, 1996). The efforts of air quality management establishments at doing this have largely been unrealized because of the unavailability of grade data for actual implementation, if grade factors are incorporated in the models. The result of this research, by making it possible to acquire roadway grade data, will enable the development of model algorithms that incorporate roadway grade effects, since it can be readily implemented in practice. Also, since the grade databases developed by this methodology are spatially referenced, it is possible to utilize them in the emerging GIS-based emission models for the spatial allocation of emissions production.

The military uses of fiber optic gyroscope and GPS technologies in guidance systems are widely known. Until recently both technologies have not been widely available to the public because of the military implications. Lately, such concerns have lessened and the utilization of the GPS technology in civil applications is becoming common place. This research has opened up a new area of application for these technologies that has hitherto not been used. It has contributed in furthering the understanding of potential applications for both the GPS and gyroscope technologies.
7.2 Limitations of the Methodology

As one of the major objectives of the research, a calibration model was developed and used to convert the raw gyroscope pitch data to actual road grade values. The development and use of the model and, the implementation of the methodology is subject to some limitations. These limitations are both theoretical and practical.

7.2.1 Theoretical Limitations

7.2.1.1 General Limitations of Predictive Models

In developing a predictive model, it is difficult to ascertain and include all the pertinent variables. This inability to control and account for all the variables gives rise to uncertainties in the predictive accuracy of the models. The calibration model developed in this research is no exception.

In developing the calibration models, the gyroscope reading was interpreted as a measurement of the roadway grade. Why this is so was demonstrated by establishing the theoretical relationship between the road grade and the gyroscope output. However, it was also shown that other factors relating to vehicle suspension and road surface conditions could significantly affect the gyroscope output. Since these factors are neither controllable nor measurable, they were not explicitly specified as variables in the model. Rather the effects were treated as error sources in the calibration data. It was noted, especially for level grade sections, that these effects can sometimes saturate and confound the actual gyroscope readings.
7.2.1.2 Limitations of the Data

Recall that the gyroscope calibration model was developed from fitting a linear regression line to a calibration data set. In as much as the collection of the calibration data was designed to incorporate normal roadway conditions, the goodness of fit of the model, as indicated by the F statistics, describes how well the regression line fits only the calibration data. It does not indicate how well the model will fit a different data, a fundamental purpose of a prediction model. The validation exercise was used to estimate how well the model can be generalized. To the extent that the calibration data is non-representative of the general road conditions, prediction with the model would include some prediction errors. To reduce these errors, collection of the calibration data should be carefully organized.

Secondly, the application of predictive models is limited to the range of the data from which the models are developed. This is so because outside the range of the data the functional form of the relationship is uncertain. This may not be a significant problem in this methodology because the required range of grade data can be decided before hand, and the calibration data can be collected which include this range. The task will then be to develop a robust calibration model that can adequately fit all the data in the desired range and minimize the prediction errors. In this research, the need to develop a suitable calibration model that minimizes the prediction errors eventually led to a reduction in the model scope from $\pm 14.6\%$ to $\pm 10.5\%$. 

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7.2.2 Practical Limitations

The practical limitations derive primarily from field implementation. As implemented in this research, the methodology involved a number of steps that renders it somewhat complex. Several of the steps in the process can be eliminated by using equipment that are more compatible. For example, by using GPS receivers from the same manufacturer for the base and rover receivers, the problem of incompatible file formats for post processing the spatial data will be eliminated. Similarly, a data logging computer with dual serial ports and a functioning mouse will transfer controls from the keyboard to the mouse, making the process easier.

Another limitation is that the calibration model developed is applicable only to grade data collected with the vehicle from which the calibration data was obtained. In other words, using the system with a different vehicle would require collecting a different set of calibration data, and developing the appropriate calibration model. This, however, is not a significant drawback as a vehicle can be dedicated for this task for the duration required to map the necessary roadways.

Also, since the methodology utilizes GPS signals to acquire spatial data, the selection of a suitable GPS receiver is important. The Workhorse GPS receiver is insensitive to minor interference and continues to give accurate spatial data under light tree canopy and other obstructions. Under dense foliage and in urban canyons, however, it suffers from interference and loss of satellite lock. If the interval of satellite loss is not long, the
spatial matching algorithm (Match.pl) can interpolate between the last two available coordinate data and allocate fairly accurate coordinates to the intervening grade data.

7.3 **Recommendations for Further Research**

This research has provided a tool by which roadway grade can be measured. However, a major issue that remains to be addressed is how the grade data should be incorporated in vehicle emission models. The relationship between grade severity and vehicle emission production has not been conclusively established, as noted in the General Accounting Office report to Congress (GAO, 1998). At what level is road grade a significant contributor to vehicle emissions, and what is the functional relationship? The theoretical relationship established in Chapter IV treated the induced gravity weight of the vehicle on a positive grade as a discrete, additional load on the vehicle engine. In that scenario the grade can be treated as an equivalent load. But the question still remains as to the incremental effect of grade on emissions. The answer to these questions will help in determining the form in which the grade data can be utilized.

As a starting point, two different approaches are suggested. In one case, the grade may be incorporated as a discrete, point-by-point variable in the Federal Test Procedure. This would be appropriate where the incremental change in vehicle emission with grade severity is relatively large. The second approach will incorporate the grade in broad classifications such as "level", "rolling", and "mountainous" as is the practice in highway
design. In the latter case, the cut-off points between the grade classifications will be
determined from the theoretical and empirical relationships between road grade and
emissions. The grade data collected by the methodology developed in this research is
already in a form that it can be used in either approach.

The vehicle suspension effects remain a major source of error in the data. A study that
can calibrate the test vehicle suspensions, or at least characterize it in a way that it can be
entered as a predictor variable in the calibration model, will go a long way towards
improving the predictive ability of the model.

7.4 General Comments About the Methodology

1. It is recommended that road grade data collection be undertaken only in light
   traffic conditions. That way it will be easier to maintain a steady vehicle speed
   without frequent stops and starts. The deceleration and acceleration that
   accompanies vehicle stops and starts usually creates a jolt that can magnify the
   suspension effect errors.

2. The effect of driver behavior (or driving style) was not investigated as a part of
   this research. But this can be a factor in the quality of the grade data. Until this is
   investigated, it is recommended that the same driver be used for collecting both
   the calibration data and the actual grade data.
3. The data analysis exercise of Chapter V seem to have established two sections where the interpretation of the gyroscope output may be problematic. From Figure 5-1 it is evident that the functional relationship between grade and gyroscope output is non-linear at high grades, both positive and negative. There seem to be an elongated S shape to the data when taken at the original limits of ±14.6%. The tapering off becomes discernible at a point higher than ±10.0%. This will explain why there were large prediction errors with the initial model developed for the full data, and justifies trimming the model scope to ±10.5% grade, a range where the relationship appears to be linear.

The second is the level grade section where the inherent error in the gyroscope appear to saturate the actual grade readings. There is no obvious grade point where this can be limited to, but the initial test for the gyroscope showed that on a level grade (about 0.0%), more than 75.0% of the output fall within ±0.5, with a total range of +1.296 to −1.35. Grade sections with gyroscope readings in this range will tend to have more prediction errors than at higher grade sections.

4. All related computer software developed in the course of this research to run different aspects of the methodology, and the GIS-based grade database of selected Atlanta region roads are available on request from the Transportation Group at Georgia Tech School of Civil and Environmental Engineering, or from the author.
APPENDIX A

SYSTEM COMPONENT SPECIFICATIONS
A-1  DMU-FIBER OPTIC GYROSCOPE SPECIFICATIONS:

Power Requirement:

Input Supply Voltage  15 - 30 Volts DC
Input Supply Current  1.0 Amp (max)

Operating Temperature Range:

Operating Temperature Range -25 to +60 °C
Storage Temperature Range -55 to +70 °C

Packaging:  Aluminum housing (5” X 5” X 4”)

Weight:  50.0 oz.

<table>
<thead>
<tr>
<th>Performance:</th>
<th>0.5° RMS</th>
<th>Application Dependent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch, Roll Angle: Dynamic Accuracy</td>
<td>0.1° RMS</td>
<td>Typical</td>
</tr>
<tr>
<td>Repeatability</td>
<td>&lt; 1% FS</td>
<td>FS Pitch = 90°</td>
</tr>
<tr>
<td>Linearity</td>
<td></td>
<td>FS Roll = 180°</td>
</tr>
<tr>
<td>Full Scale Span (analog outputs)</td>
<td>± 4.096 VDC</td>
<td>FS Pitch = 90°</td>
</tr>
<tr>
<td>Analog Data Update Rate</td>
<td>TBD Hz</td>
<td>FS Roll = 90°</td>
</tr>
<tr>
<td>Digital Data Update Rate</td>
<td>TBD Hz</td>
<td>See below for details</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Raw Sensor Performance:</th>
<th>F. O. G.</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Full Scale Ranges</td>
<td>200 °/sec</td>
<td>± 2.0 G</td>
</tr>
<tr>
<td>Full Scale Span (analog outputs)</td>
<td>N/A</td>
<td>0 to 5 V DC</td>
</tr>
<tr>
<td>Full Scale Span (digital outputs)</td>
<td>-32.768 to +32.787</td>
<td>-32.768 to +32.787</td>
</tr>
<tr>
<td>Scale Factor Calibration</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>DC – 100 Hz</td>
<td>DC – 100 Hz</td>
</tr>
<tr>
<td>Linearity</td>
<td>0.2% of FS</td>
<td>0.2% of FS</td>
</tr>
<tr>
<td>Bias Stability (Room)</td>
<td>± 0.1 °/sec</td>
<td>± 1.5 mG</td>
</tr>
<tr>
<td>Bias Stability (-40 to 85)</td>
<td>± 0.1 °/sec</td>
<td>± 30 mG</td>
</tr>
<tr>
<td>Alignment (to enclosure)</td>
<td>&lt; 1 °</td>
<td>&lt; 1 °</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.0002</td>
<td>1.5 mG</td>
</tr>
<tr>
<td>Random Walk</td>
<td>4.25 °/SqrtHr (max)</td>
<td></td>
</tr>
</tbody>
</table>

Temperature Sensor Output:

201
Range: -40 to 85 °C
Accuracy: ± 2% of FS
Linearity: ± 1% of FS

Mechanical Shock and Vibration:
- Shock: 1000 G (1 ms half sine wave)
- Vibration: 10 G RMS to 2 KHz

<table>
<thead>
<tr>
<th>Data Packet Format</th>
<th>Vertical Gyro Mode</th>
<th>Scaled Sensor Mode</th>
<th>Voltage Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Header</td>
<td>Header (255)</td>
<td>Header (255)</td>
</tr>
<tr>
<td>1</td>
<td>Roll (MSB)</td>
<td>Angular Rate X (MSB)</td>
<td>Gyro Voltage X (MSB)</td>
</tr>
<tr>
<td>2</td>
<td>Roll (LSB)</td>
<td>Angular Rate X (LSB)</td>
<td>Gyro Voltage X (LSB)</td>
</tr>
<tr>
<td>3</td>
<td>Pitch (MSB)</td>
<td>Angular Rate Y (MSB)</td>
<td>Gyro Voltage Y (MSB)</td>
</tr>
<tr>
<td>4</td>
<td>Pitch (LSB)</td>
<td>Angular Rate Y (LSB)</td>
<td>Gyro Voltage Y (LSB)</td>
</tr>
<tr>
<td>5</td>
<td>Roll Rate (MSB)</td>
<td>Angular Rate Z (MSB)</td>
<td>Gyro Voltage Z (MSB)</td>
</tr>
<tr>
<td>6</td>
<td>Roll Rate (LSB)</td>
<td>Angular Rate Z (LSB)</td>
<td>Gyro Voltage Z (LSB)</td>
</tr>
<tr>
<td>7</td>
<td>Pitch Rate (MSB)</td>
<td>Acceleration X (MSB)</td>
<td>Accelerometer Voltage X (MSB)</td>
</tr>
<tr>
<td>8</td>
<td>Pitch Rate (LSB)</td>
<td>Acceleration X (LSB)</td>
<td>Accelerometer Voltage X (LSB)</td>
</tr>
<tr>
<td>9</td>
<td>Yaw Rate (MSB)</td>
<td>Acceleration Y (MSB)</td>
<td>Accelerometer Voltage Y (MSB)</td>
</tr>
<tr>
<td>10</td>
<td>Yaw Rate (LSB)</td>
<td>Acceleration Y (LSB)</td>
<td>Accelerometer Voltage Y (LSB)</td>
</tr>
<tr>
<td>11</td>
<td>Acceleration X (MSB)</td>
<td>Acceleration Z (MSB)</td>
<td>Accelerometer Voltage Z (MSB)</td>
</tr>
<tr>
<td>12</td>
<td>Acceleration X (LSB)</td>
<td>Acceleration Z (LSB)</td>
<td>Accelerometer Voltage Z (LSB)</td>
</tr>
<tr>
<td>13</td>
<td>Acceleration Y (MSB)</td>
<td>Temp Sensor Voltage (MSB)</td>
<td>Temp Sensor Voltage (MSB)</td>
</tr>
<tr>
<td>14</td>
<td>Acceleration Y (LSB)</td>
<td>Temp Sensor Voltage (LSB)</td>
<td>Temp Sensor Voltage (LSB)</td>
</tr>
<tr>
<td>15</td>
<td>Acceleration Z (MSB)</td>
<td>Time (MSB)</td>
<td>Time (MSB)</td>
</tr>
<tr>
<td>16</td>
<td>Acceleration Z (LSB)</td>
<td>Time (LSB)</td>
<td>Time (LSB)</td>
</tr>
<tr>
<td>17</td>
<td>Temp Sensor Voltage (MSB)</td>
<td>Checksum</td>
<td>Checksum</td>
</tr>
<tr>
<td>18</td>
<td>Temp Sensor Voltage (LSB)</td>
<td>Checksum</td>
<td>Checksum</td>
</tr>
<tr>
<td>19</td>
<td>Time (MSB)</td>
<td>Checksum</td>
<td>Checksum</td>
</tr>
<tr>
<td>20</td>
<td>Time (LSB)</td>
<td>Checksum</td>
<td>Checksum</td>
</tr>
<tr>
<td>21</td>
<td>Checksum</td>
<td>Checksum</td>
<td>Checksum</td>
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</table>
### Processing Activity Timing

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Estimated Conversion Time (T1)</th>
<th>Estimated Processing Time (T2)</th>
<th>Transfer Time (T3)</th>
<th>Estimated Total Time (Sum)</th>
<th>Estimated Data Rate Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Sensor:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>3.2 ms</td>
<td>0.5 ms</td>
<td>4.7 ms</td>
<td>8.4 ms</td>
<td>125 Hz</td>
</tr>
<tr>
<td>Scaled</td>
<td>3.2 ms</td>
<td>0.5 ms</td>
<td>4.7 ms</td>
<td>8.4 ms</td>
<td>125 Hz</td>
</tr>
<tr>
<td>Vertical Gyro:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital</td>
<td>3.2 ms</td>
<td>1.5 ms</td>
<td>5.2 ms</td>
<td>10 ms</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Analog</td>
<td>3.2 ms</td>
<td>1.5 ms</td>
<td>-----</td>
<td>4.7 ms</td>
<td>200 Hz</td>
</tr>
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</table>

### Connector Pin Out

<table>
<thead>
<tr>
<th>Pin</th>
<th>Signal</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>RS-232 Transmit Data</td>
</tr>
<tr>
<td>2</td>
<td>RS-232 Receive Data</td>
</tr>
<tr>
<td>3</td>
<td>Vcc</td>
</tr>
<tr>
<td>4</td>
<td>GND</td>
</tr>
<tr>
<td>5</td>
<td>X-axis acceleration analog voltage</td>
</tr>
<tr>
<td>6</td>
<td>Y-axis acceleration analog voltage</td>
</tr>
<tr>
<td>7</td>
<td>Z-axis acceleration analog voltage</td>
</tr>
<tr>
<td>8</td>
<td>Roll rate analog voltage</td>
</tr>
<tr>
<td>9</td>
<td>Pitch rate analog voltage</td>
</tr>
<tr>
<td>10</td>
<td>Yaw rate analog voltage</td>
</tr>
<tr>
<td>11</td>
<td>Timing pulse</td>
</tr>
<tr>
<td>12</td>
<td>Roll analog voltage</td>
</tr>
<tr>
<td>13</td>
<td>Pitch analog voltage</td>
</tr>
<tr>
<td>14</td>
<td>Unused</td>
</tr>
<tr>
<td>15</td>
<td>Unused</td>
</tr>
</tbody>
</table>
GPS WORKHORSE RECEIVER SPECIFICATIONS:

Power Requirement:

Operating Voltage: 4.75 - 5.25 Volts DC, 50 m Vp-p ripple
Operating Current: 230 mA typical at 5V, 275 mA max at 5.25 V
Standby Voltage: 2.5 - 5.0 Volts DC
Standby Current: 60 µA max

Environmental:

Operating Temperature: -30 to +85 °C (without on-board battery)
                           -20 to +60 °C (with on-board battery)
Storage Temperature:  -30 to +85 °C (without on-board battery)
                           -20 to +60 °C (with on-board battery)
Humidity: 95% RH, non-condensing

Packaging: Aluminum housing (2.0” X 3.25” X 0.64”)

Weight: 19.0 oz.

Receiver Architecture:

- 8 Channel
- L1 1575.42 MHz
- C/A Code (1.023 MHz chip rate)
- Code plus carrier tracking (carrier-aided tracking)

Tracking Capability: 8 satellite vehicles simultaneously

Communication:

Signal Level: TTL

Output Messages: - Latitude, Longitude, Height, Velocity, Heading,
                  Satellite Tracking Status
                  - NMEA-0813 Version 2.00 (GGA, RMC, GGL, GSA)
                  - LORAN emulation mode
                  - Software Selectable
                  - Dual Serial Port
### Performance Characteristics

#### Dynamics:
- **Velocity:** 1000 m/s when altitude less than 18 km
- **Altitude:** 18 km for velocities greater than 514 m/s
- **Acceleration:** 4.0 g

#### Antenna:
- Accepts active and passive antennas

#### Acquisition Time (Time To First Fix – TTFF):
- 22 seconds typical TTFF (with current almanac, position, time, and ephemeris)
- 48 seconds typical TTFF (with current almanac, position, and time)
- 2.5 seconds typical re-acquire

#### Accuracy:
- **Position:**
  - Less than 25.0 meters, SEP (without AS)
  - Up to 100.0 meters (with AS)
  - Up to 2-5 centimeters with differential correction

#### Datums:
- 49 standard datums, 2 user defined, default is WGS-84
APPENDIX B

DOCUMENTATION FOR RELATED SOFTWARE PROGRAMS
B.1.1 GPS-gyro-combo.vi  (This page and next):
B.1.2 Log WHII.vi (This page and next):

Connector Pane

Front Panel
B.1.3 DMU Example.vi (This page and next):

Connector Pane

Log Data
  port ID
File Name
  1
stop
DMU Example.vi

Front Panel

File Name
  default.csv
port ID
  COM1
Log Data
  OFF

VG outputs

<table>
<thead>
<tr>
<th>roll</th>
<th>pitch</th>
<th>roll rate</th>
<th>pitch rate</th>
<th>yaw rate</th>
<th>accel X</th>
<th>accel Y</th>
<th>accel Z</th>
<th>temp</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
B-2: PERL PROGRAMS

B.2.1: Batch.pl

# This is a batch file that runs the other three perl programs
# clean_gyro.pl, clean_gps.pl, and match_gps.pl, one after the other
# to perform the entire processing step with a single command

#!/usr/bin/perl
use Cwd;

# Command to use this program is:
# batch.pl gps_input_file gyro_input_file matched_output_file
# for example,
# perl batch.pl I285a.dps I285a.txt I285a_matched.txt

if(!@ARGV){
    print "\nUsage:\n";
    print "\tper batch.pl gps_file gyro_file matched.txt\n";
    print "\toutputs:\n\nt\ncleaned.txt\n\ttmodels.out\n\n";
    exit;
}

# Get the input and output file names from the command line arguments
$dir = cwd;
print "Local directory is \: $dir\n";

# Set variable for gps input file (first variable on command line)
$input1 = shift @ARGV;

# Set variable for gyro input file (second variable on command line)
$input2 = shift @ARGV;

# Set variable for output file (third variable on command line)
$output = shift @ARGV;

$cmd = "perl clean_gps.pl $input1 gps.txt";
print $cmd."\n"

$cmd = "perl clean_gyro.pl $input2 pitch.txt";
print $cmd."\n"

$cmd = "perl match_gps.pl gps.txt pitch.txt matched.txt";
print $cmd."\n"

$cmd = "perl cleaner.pl matched.txt premodel.out";
print $cmd."\n"

$cmd = "perl models.pl premodel.out $output";
print $cmd."\n";
B.2.2: Clean-gps.pl

#!perl

# The command to use the program at the DOS prompt is:
# clean_gps.pl input_file output_file
# for example
# clean_gps.pl I285a.dpa I285a_gps.txt

# Get the input and output file names from the command line arguments

# Set variable for input file (first variable on the command line)
$input = shift @ARGV;

# Set variable for output file (second variable from the command line)
$output = shift @ARGV;

# Definition of $iter as a global variable
$iter = 0;

# Open the input file and the output file
open(INPUT, "< $input") or die "Couldn't open $input for reading: $!\n";
open (OUTPUT, "> $output") or die "Could not open $output for writing: $!\n";

while (<INPUT>) {
    # read line by line of the input file
    my @array = (); # clear the array for this line
    next if( substr($_,2,1) ne "," );
    my @array = split(","); # assign all values of line into an array
    my @array = Remove_Space(@array); # remove all spaces in array
    @array = Process_Line(@array);
    PrintArray(@array);
}

close(INPUT); # close the input file
close(OUTPUT); # close the output file
### SUBROUTINES

sub Process_Line {  # To choose the required columns
    my @array = @_;  
    my @new = ();  

    $str = $array[0]."\:".$array[1]."\:".$array[2];  
    push @new, $str;  
    $str = substr($array[4],3);  
    push @new, $str;  
    $str = substr($array[5],3);  
    push @new, $str;  

    return @new;  
}

sub Remove_Space {  
    my @out = @_;  
    for (@out) {  
        s/\s+//;  
        s/\s+$//;  
    }  

    return wantarray ? @out : $out[0];  
}

sub PrintArray {  # creates a comma delimited line of output  
    # this is called iteratively to append data  
    # to the output file  
    my @array = @_;  
    my $last_data = $#array;  # get the number of last item in array  
    for my $i (0..$last_data) {  
        print OUTPUT "$array[($i)]";  
        if ($i < ($last_data)) {  
            print OUTPUT ",";  
        } else {  
            print OUTPUT "\n";  
        }  
    }  
}

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B.2.3: Clean-gyro.pl

# This program formats the gyroscope data for use in matching with # the GPS data.
# NOTE: MANUALLY REMOVE ALL HEADER LINES AND POORLY FORMATTED # DATA AT THE BEGINNING OF THE FILE BEFORE RUNNING THIS PROGRAM # It discounts the first two header lines at the beginning of file #

#!/usr/bin/perl

# the command to use the program at the DOS prompt is:
# clean_gyro.pl input_file output_file
# for example
# clean_gyro.pl I285a.txt I285a_pitch.txt

# get the input and output file names from the command line arguments

# set variable for input file (first variable on the command line)
$in = shift @ARGV;

# set variable for output file (second variable from the command line)
$out = shift @ARGV;

# definition of $iter and $n as global variables
$n = 10;

# open the input file
open(INPUT, "< $in") or die "Couldn't open $in for reading: $!
'

while (<INPUT>) {
  # read line by line of the input file
  next if( substr($_,2,1) ne "\n" );
  my @array = (); # clear the array for this line
  my @array = split("\t"); # assign all values of line into array
  my @array = Remove_Space(@array); # remove all spaces in array
  @array = Process_Line(@array);
}

# close the input file

# Print the array after the data has been processed into it.
&Print_Pitch;
### SUBROUTINES

```perl
sub Print_Pitch {  # printing the whole array
    open (OUTPUT, ">$output");  # open output file
    for ( $i = $n ; $i <= ($max_iter-$n) ; $i++ ) {
        print OUTPUT
"$pitch[$i][0],$pitch[$i][1],$pitch[$i][2],$pitch[$i][3]\n";
    }
    close(OUTPUT);  # close the output file
}  # end Print_Pitch

sub Process_Line {  # just putting the stuff into a big 2D array
    my @array = @_;  
    my @new = ();
    
    $pitch[$iter][0] = $array[1];
    $pitch[$iter][1] = $array[3];
    $pitch[$iter][2] = $array[3];
    $pitch[$iter][3] = $array[5];
    $iter++;
    $max_iter = $iter;
    return @array;
}

sub Remove_Space {  
    my @out = @_;  
    for (@out) {
        s/\s+//;
    }  
    return wantarray ? @out : $out[0];
}

sub PrintArray {  
    my @array = @_;  
    my $last_data = $#array;  # get number of the last item in array
    print OUTPUT "$last_data\n";
    for my $i (0..$last_data) {
        print OUTPUT "$array[$i]\n";
        if ($i < ($last_data)) {
            print OUTPUT ",\n";
        } else {
            print OUTPUT \n";
        }
    }
    }  
```
B.2.4: Match gps-gyro.pl

```
# This program matches the gps file to the gyroscope file, and
# performs the necessary linear interpolations for assigning the
# appropriate coordinates (longitude and latitude) to intervening
# grade data points.

#!/usr/bin/perl

# The command to use the program at the DOS prompt is:
# match_gps.pl gps_input_file gyro_input_file matched_output_file
# for example:
# match_gps.pl I285a_gps.txt I285a_pitch.txt I285a_matched.txt

# Get the input and output file names from the command line arguments

$Input1 = shift @ARGV;
$Input2 = shift @ARGV;
$Output  = shift @ARGV;

# definition of $iter as a global variable
$iter = 0;

# open the first (gps) input file
open(INPUT1, "<$Input1") or die "Couldn't open $Input1 for reading: $!\n"; # if no input # file, Die!

while (<INPUT1>) {  # read line by line of the input file
my @array = ();  # clear the array for this line
my @array = split("","");  # assign all values of line into array
my @array = Remove_Space(@array);  # remove all spaces in array
array = Create_Gps(@array);
}
close(INPUT1);  # close the input file

$iter = 0;

# open the second (gyro) input file

open(INPUT2, "<$Input2") or die "Couldn't open $Input2 for reading: $!\n"; # if no input # file, Die!
```
while (<INPUT2>) {  # read line by line of the input file
    my @array = ();  # clear the array for this line
    my @array = split(",",";  # assign all values of line into array
    my @array = Remove_Space(@array);  # remove all spaces in array
    @array = Create_Pitch(@array);
}
close(INPUT2);  # close the input file

&Match;
&doInterpolation;
&Print_Pitch;

SUBROUTINES

sub Create_Pitch {  # putting the gyro readings into the 2D pitch array
    my @array = @_;

    $pitch[Siter][0] = $array[0];
    $pitch[Siter][1] = $array[1];
    $pitch[Siter][2] = $array[2];
    $pitch[Siter][3] = $array[3];
    $iter++;
    $max_iter = $iter;
    return @array;
}

sub Create_Gps {  # putting the gps readings into the 2D gps array
    my @array = @_;

    $gps[Siter][0] = $array[0];
    $gps[Siter][1] = $array[1];
    $gps[Siter][2] = $array[2];
    $iter++;
    $max_iter = $iter;
    return @array;
}

sub convert_to_secs {  # conversion from time format to numeric format
    my $in_secs;
    $in_secs = substr($_[0],0,2) * 3600 + substr($_[0],3,2) * 60 +
               substr($_[0],5);
    return $in_secs;
}

# end sub convert to secs
sub convert_to_time( # conversion to time format from numeric format
        my $in_time;
        my $hours;
        my $minutes;
        my $seconds;

        $hours = $0 / 3600;
        ($hours,$minutes) = split ( '/\./', $hours );
        $minutes = "0\.".$minutes;
        $minutes = $minutes * 60;
        ($minutes,$seconds ) = split ( '/\./', $minutes ) ;
        $seconds = "0\.".$seconds;
        $seconds = $seconds * 60;

        $in_time = $hours."\:".$minutes."\:".$seconds;

        return $in_time;
    ) # end sub convert to time

sub doInterpolation( # do interpolation
    my $iprime=0;
    my $jprime=0;
    my $last_time;
    my $current_time;
    my $last_time_in_secs;
    my $current_time_in_secs;
    my $initial_lat;
    my $initial_long;
    my $last_lat;
    my $last_long;
    my $interp_lat;
    my $interp_long;

    for ( $iprime = 1; $iprime < $max_iter; $iprime++ ){
        $last_time   = $pitch[$iprime-1][0];
        $current_time = $pitch[$iprime][0];
        $initial_lat  = $pitch[$iprime][4];
        $initial_long = $pitch[$iprime][5];
        $last_lat    = $pitch[$iprime-1][4];
        $last_long   = $pitch[$iprime-1][5];

        $last_time_in_secs = convert_to_secs( $last_time );
        $current_time_in_secs = convert_to_secs( $current_time );

        if( $current_time eq $last_time ){
$i_{\text{static}}++;
} # end of if condition
else {
    if ( ($current\_time\_in\_secs - $last\_time\_in\_secs) < 2.0 ) {

        $\text{interp\_lat} = ( \text{convert\_to\_secs(} \text{\$initial\_lat } ) -
        \text{convert\_to\_secs(} \text{\$last\_lat } ) ) / \$i_{\text{static}};
        \text{interp\_long} = ( \text{convert\_to\_secs(} \text{\$initial\_long } ) -
        \text{convert\_to\_secs(} \text{\$last\_long } ) ) / \$i_{\text{static}};

        for ( \$jprime = ($i_{\text{prime}} - \$i_{\text{static}}); \$jprime < $i_{\text{prime}};
            \$jprime++ ) {

            \text{if ( convert\_to\_secs(} \text{\$last\_lat } == 0 ) { 
                \text{pitch}[\$jprime][4] = "NA";
                \text{pitch}[\$jprime][5] = "NA"
            } # to ensure that there is a valid gps reading corresponding to the datapoint

            else {
                \text{temp1} = \text{convert\_to\_secs(} \text{\$last\_lat } ) + $\text{interp\_lat}
                \text{* (} \text{$i_{\text{prime}} - (} \text{$i_{\text{prime}} - \$i_{\text{static}}) ) ;
                \text{temp2} = \text{convert\_to\_secs(} \text{\$last\_long } ) + $\text{interp\_long} \text{* (} \text{$i_{\text{prime}} - (} \text{$i_{\text{prime}} - \$i_{\text{static}}) ) ;
                \text{pitch}[\$jprime][4] = \text{convert\_to\_time(} \text{\$temp1);}
                \text{pitch}[\$jprime][5] = \text{convert\_to\_time(} \text{\$temp2);}
            } # end of else

        } # end of for loop

    } # ensuring that there is no discontinuity in gyro data
else {
# do not interpolate
    # leave first value intact and make the rest NA
        for ( \$jprime = ($i_{\text{prime}} - \$i_{\text{static}} + 1); \$jprime < $i_{\text{prime}}; \$jprime++ ) {
            \text{pitch}[\$jprime][4] = "NA";
            \text{pitch}[\$jprime][5] = "NA"
        } # end of for loop

    } # end of embedded else
    \$i_{\text{static}} = 1;

} # end of else condition

} # end for loop
} # end sub doInterpolation

sub Match{ 
    my $i_{\text{prime}}=0;
    my $j_{\text{prime}}=0;
    my $\text{flag} = 0;
}
my $iterations = 0;
my $maximum_iterations = 10;

for ( $iprime = 0 ; $iprime < $max_iter ; $iprime++ ){
    $flag = 0;
    $iterations = 0;
    $pitch_time = $pitch[$iprime][0];
    chomp($pitch_time);

    while( ($flag eq "0") && ($iterations < $maximum_iterations) ){
        $gps_time = $gps[$iprime][0];
        # cleaning up any unwanted characters at end of string
        chomp($gps_time);

        # This ensures that every gyro data point is represented,
        # if there is no gps reading corresponding to a gyro datapoint,
        # it is set to zero now. Later, during further processing,
        # it will be resetted to “NA”;
        if("$gps_time" eq "$pitch_time"){
            $pitch[$iprime][4] = $gps[$iprime][1];
            $pitch[$iprime][5] = $gps[$iprime][2];
            $flag = 1;
        } else {
            $pitch[$iprime][4] = "0";
            $pitch[$iprime][5] = "0";
            $iprime++;
            $iterations++;
        }

        if($iterations == $maximum_iterations) {
            $iprime -= $maximum_iterations;
        }
    }
}

} # end sub Match

sub Print_Pitch {
    my $i=0;
    open (OUTPUT, "> $output"); # open output file
    print OUTPUT "Timestamp,Original Pitch,Corrected Pitch,Roll,Longitude\n";
    for ( $i = 0 ; $i < $max_iter ; $i++ ) { # change
        if ( $pitch[$i][4] ne "NA") { # change
            print OUTPUT "$pitch[$i][0],$pitch[$i][1],$pitch[$i][2],$pitch[$i][3],$pitch[$i][4]
            ,$pitch[$i][5] \n";
        }
    }
    close(OUTPUT); # close the output file
} # end Print_Pitch
sub Remove_Space {
    my @out = @_; 
    for (@out) {
        s/^\s+//; 
        s/\s+$//; 
    }
    return wantarray ? @out : $out[0];
}
B.2.5: Model.pl

# This program applies the calibration model to the pitch data, and #
# converts it to a percentage grade value. It also screens the pitch #
data to remove all values outside the model range.                     #

# Define the gyroscope data range within which the model is applicable.
$lower_limit = -6.278;
$upper_limit = 7.361;

# Get the name of the matched file as a parameter from command line
$matched_file = @ARGV[0];
if (!$matched_file) { $matched_file = "premodel.txt" }
$output_file = @ARGV[1];
if (!$output_file) { $output_file = "modeled.out" }

# open the file and read one line at a time
open( IN, "<$matched_file" );
open( OUT, ">$output_file" );

$j=0;
$i=0;
while(<IN>){
    next if( substr($_,2,1) ne ";" );
    $j++;
    chomp;
    $lastpitch = $pitch;
    ($timestamp, $latitude, $longitude, $pitch,$signvar) = split(/,/,$_);
    if ($j eq "1"){
        $lastpitch = $pitch;
    }
    next if ($j eq "1");

    $grade = "NULL";
    $grade = &signed_model($pitch,$signvar);
    if ($grade ne "NULL"){
        if($i != 0){
            print OUT "$i,$latitude,$longitude,$grade\n";
        }
        $i++;
    }
}
close IN;
close OUT;
sub signed_model{
    my $reading = $_[0];
    my $signvar = $_[1];
    $grade = -0.4950 + 1.5954 * $reading
           - 0.3256 * $signvar;
    return $grade;
}
B.2.6: Cleaner.pl

```
# This program formats the final output file -
# From:
# Timestamp,Original Pitch,Corrected Pitch,Roll,Latitude,Longitude
# To:
# Timestamp,Corrected Pitch,Latitude,Longitude

# Get the name of the matched file as a parameter from command line

$matched_file = $ARGV[0];
if (!defined($matched_file) ( $matched_file = "matched.txt" )
$output_file = $ARGV[1];
if (!defined($output_file) ( $output_file = "premodel.out" )

open( IN, "<$matched_file" );
open( OUT, ">$output_file" );
print OUT "Timestamp,Latitude,Longitude,Grade\n";
while(<IN>){

    next if( substr($_,2,1) ne ":");
    chomp;
    ($timestamp, $pitch_original, $pitch_corrected, $roll, $latitude, $longitude) = split(/,/,);
    if ( $pitch_corrected >= 0 ) { $signvar = 1; }
    else { $signvar = 0; }
    print OUT "$timestamp,$latitude,$longitude,$pitch_corrected,$signvar\n";
}
close IN;
close OUT;
```

```
APPENDIX C

DATA ANALYSIS

AND MODEL DEVELOPMENT
Model C1:

Table C1-a: Summary of Simple Linear Model with Full Data

```r
> summary(ugrd.lm)

Call: lm(formula = Grade ~ Reading, data = ugrdata)
Residuals:
     Min      1Q  Median       3Q      Max
-2.8500 -0.8351  0.001046  0.8049  3.009

Coefficients:         Value  Std. Error  t value Pr(>|t|)
(Intercept)  -0.7779       0.0666   -11.6782  0.0000
Reading       1.5393       0.0136    113.1110  0.0000

Residual standard error: 1.124 on 286 degrees of freedom
Multiple R-Squared: 0.9781
F-statistic: 12790 on 1 and 286 degrees of freedom, the p-value is 0

Correlation of Coefficients:
  (Intercept) Reading -0.1032

The model is:

Grade = -0.7779 + 1.5393 * Reading
```
Figure C1-a: Residuals Plot: Simple Linear Model With Full Data

Figure C1-b: Sqrt (Abs Residual) vs. Fitted: Simple Model With Full Data
Figure C1-c: Fitted Values Plot: Simple Model with Full Data

Figure C1-d: Quantiles of Standard Normal: Simple Model With Full Data
Figure C1-e: Residuals – Fitted Values Plot: Linear Model With Full Data

Figure C1-f: Cook’s Distance Plot: Linear Model With Full Data
Model C2:

Table C2-a: Summary of Remedial Model with Full Data (Reading + Vehicle Speed Variables)

```
> summary(Grade.lm)

Call: lm(formula = Grade ~ Reading + Speed)
Residuals:
     Min      1Q  Median       3Q      Max
-3.7750 -0.7836  0.007429  0.8777  3.1540

Coefficients:     Value Std. Error t value Pr(|t|)
(Intercept)    -1.0371  0.4450   -2.3306  0.0205
Reading         1.6030  0.0156    102.8243  0.0000
Speed          -0.0027  0.0144   -0.1841  0.8541

Residual standard error: 1.231 on 286 degrees of freedom
Multiple R-Squared:  0.9748
F-statistic: 5287 on 2 and 273 degrees of freedom,
the p-value is 0

Correlation of Coefficients:
   (Intercept) Reading
Reading   -0.0308
Speed     -0.9857

> Model-C2 is:

    Grade = -1.0371 + 1.603*Reading - 0.0027*Speed
```
Figure C2-a: All Diagnostic Plots: Remedial Model (Reading + Speed as Variable)
Figure C2-b: Pairwise Plot of Grade, Reading, and Speed
C.1 Calculation of the Durbin-Watson Test Statistic for Model-1:

\[
D = \frac{\sum_{i=2}^{n} (e_i - e_{i-1})^2}{\sum_{i=1}^{n} e_i^2}
\]

\[
D = \frac{516.32}{357.53} = 1.444
\]

At a level of significance, \( \alpha = 0.05 \), and \( n = 100 \) (our sample size is actually 288 but the D-W table gives values only to 100)

Read \( D_U = 1.69 \)
And \( D_L = 1.65 \)

Since \( D = 1.444 < D_L = 1.65 \), we conclude \( H_0: \rho > 0 \)

This formally confirms the data is spatially correlated since it concludes that the correlation parameter \( \rho \) is greater than zero.

C.2 Calculation of the Cochrane-Orcutt estimate of \( \rho \):

\[
r = \frac{\sum_{i=2}^{n} e_{i-1}e_i}{\sum_{i=2}^{n} e_i^2}
\]

\[
r = \frac{101.02}{357.53} = 0.283
\]

\[\rightarrow \] \( T\text{grade}_i = \text{Grade}_i - 0.283*\text{Grade}_{i-1} \)
\[\rightarrow \] \( T\text{reading}_i = \text{Reading}_i - 0.283*\text{Reading}_{i-1} \)

where:
\( T\text{grade} \) = transformed grade value
\( T\text{reading} \) = transformed reading value

The resulting OLS regression function (output shown below as Model-C3) is:

\[
T\text{grade}_p' = -0.5433 + 1.517*T\text{reading}'
\]

C.1
2nd Iteration:

Calculation of the Durbin-Watson test statistic for this model gives:

\[ D = \frac{689.9292}{327.58} = 2.106 \]

And at \( \alpha = 0.05 \), \( D_U = 1.69 \)
\( D_L = 1.65 \)

\[ \Rightarrow D = 2.106 > D_U = 1.69, \text{ therefore conclude } H_0: \rho = 0 \]

This means that the transformation has successfully eliminated the trend in the data, and it can be concluded that the residuals of the transformed variable model are random.

Back Calculation to Original Variables:

Recall from Equation 5.19:

\[ b_{0'} = b_0 / (1 - r), \text{ and } \]
\[ b_1 = b_1' \]

From Equation C.1, \( b_0 = \frac{-0.5433}{(1 - 0.283)} = -0.7577 \) \( \text{C.2} \)
\[ b_1 = 1.517 \] \( \text{C.3} \)

\[ \Rightarrow \text{ The regression function is:} \]

\[ \text{Grade}_{1p1} = -0.7577 + 1.517 \times \text{Reading} \] \( \text{C.4} \)
Model C3:

Table C3-a: Transformed Variables Model With Full Data
(Cochrane-Orcutt Procedure)

```
> summary(tgrd.lm)

Call: lm(formula = Tgrade ~ Treading, data = tgrdata)
Residuals:
     Min      1Q  Median      3Q     Max
-2.587 -0.7431 -0.08967 0.8448 2.975

Coefficients:
                Value Std. Error t value Pr(>|t|)
(Intercept)   -0.5433    0.0636   -8.5484    0.0000
Treading        1.5170    0.0181    83.7732    0.0000

Residual standard error: 1.072 on 285 degrees of freedom
Multiple R-Squared: 0.961
F-statistic: 7018 on 1 and 285 degrees of freedom,
the p-value is 0

Correlation of Coefficients:
              (Intercept)
Treading -0.0898
```

Model C3 is:

\[
T_{\text{grade}} = -0.5433 + 1.517 \times T_{\text{reading}}
\]
Figure C3-a: Residuals Plot: Cochrane-Orcutt Transformed Variables Model

Figure C3-b: Sqrt(Abs Residual) vs Fitted: Cochrane-Orcutt Transformed Model
Figure C3-c: Fitted Values Plot: Cochrane-Orcutt Transformed Model

Figure C3-d: Quantiles of Standard Normal: Cochrane-Orcutt Model
Figure C3-e: Residuals – Fitted Plot: Cochrane-Orcutt Transformed Model

Figure C3-f: Cook’s Distance Plot: Cochrane-Orcutt Transformed Model
Model C4:

Table C4-a: Summary of Simple Linear Model with Trimmed Data

```r
> summary(trmgrd.lm)

Call: lm(formula = Grade ~ Reading, data = gradata)
Residuals:
    Min     1Q    Median     3Q    Max
-2.16 -0.7617  0.02582  0.7047  2.79

Coefficients:       Value     Std. Error   t value Pr(>|t|)
(Intercept)    -0.6455     0.0701     -9.2123  0.0000
Reading        1.5554     0.0211      73.7355  0.0000

Residual standard error: 1.05 on 226 degrees of freedom
Multiple R-Squared:  0.9601
F-statistic: 5437 on 1 and 226 degrees of freedom,     
the p-value is 0

Correlation of Coefficients:
 (Intercept)     
Reading  -0.1249
>

The Model is:

Grade = -0.6455 + 1.5554 * Reading
```
Figure C4-a: Residuals Plot: Simple Linear Model with Trimmed Data

Figure C4-b: Sqrt (Abs Residual) vs. Fitted: Simple Model with Trimmed Data
Figure C4-c: Fitted Values Plot: Simple Model With Trimmed Data

Figure C4-d: Quantiles of Standard Normal: Simple Model With Trimmed Data
Figure C4-e: Residual – Fitted Plot: Simple Model With Trimmed Data

![Fitted Values and Residuals Plot](image)

Figure C4-f: Cook’s Distance Plot: Simple Model With Trimmed Data

![Cook's Distance Plot](image)
Model C5:

Table C5-a: Summary Output for Trimmed Data Model
(Reading + Change in Reading as Predictor Variables)

```r
> summary(rcgrd.lm)

Call: lm(formula = Grade ~ Reading + Creading, data=aldatalm)
Residuals:
     Min      1Q  Median      3Q     Max
-2.3080 -0.5460 0.002793 0.5737  2.2710

Coefficients:     Estimate Std. Error t value Pr(>|t|)
(Intercept) -0.69860   0.05580  -12.515  0.00000
Reading      1.57890   0.01690   93.597  0.00000
Creading    -0.75830   0.06560  -11.559  0.00000

Residual standard error: 0.8334 on 225 degrees of freedom
Multiple R-Squared: 0.975
F-statistic: 4380 on 2 and 225 degrees of freedom,
the p-value is 0

Correlation of Coefficients:
   (Intercept) Reading
Reading -0.1335
Creading 0.0823  -0.1203
```

The Model is:

```
Grade = -0.6986 + 1.5789*Reading - 0.7583*Creading
```
Figure C5-a: Residuals Plot: Trimmed Data Model (Reading + Creading)

Figure C5-b: Sqrt (Abs Residual) vs. Fitted: Trimmed Data (Reading + Creading)
Figure C5-c: Fitted Values Plot: Trimmed Data (Reading + CReading)

Figure C5-d: Quantiles of Standard Normal: Trimmed Data (Reading+CReading)
Figure C5-e: Residual – Fitted Plot: Trimmed Data (Reading + Creading)

Figure C5-f: Cook’s Distance Plot: Trimmed Data (Reading + Creading)
Model C6:

Table C6-a: Summary Output for Trimmed Data Model
(Reading + Sign of Reading as Predictor Variables)

```r
> summary (grdmod)

Call: lm(formula = Grade ~ Reading + Signvar, data = grdrd)
Residuals:
   Min     1Q Median     3Q    Max
  -2.153  -0.7171  -0.01953  0.6993  2.75

Coefficients:
                     Value Std. Error t value Pr(>|t|)
(Intercept)      -0.4950   0.1298   -3.8124   0.0002
Reading           1.5954   0.0359   44.4412   0.0000
Signvar          -0.3256   0.2367   -1.3756   0.1703

Residual standard error: 1.048 on 225 degrees of freedom
Multiple R-Squared:  0.9604
F-statistic: 2730 on 2 and 225 degrees of freedom,
the p-value is 0

Correlation of Coefficients:
   (Intercept) Reading
Reading   0.6430          
Signvar  -0.8426  -0.8100
```

The Model is:

```
Grade = -0.4950 + 1.5954*Reading - 0.3256*Signvar
```
Figure C6-a: Residuals Plot: Trimmed Data Model (Reading + Signvar)

Figure C6-b: Sqrt (Abs Residual) vs. Fitted: Trimmed Data (Reading + Signvar)
Figure C6-c: Fitted Values Plot: Trimmed Data (Reading + Signvar)

Figure C6-d: Quantiles of Standard Normal: Trimmed Data (Reading+Signvar)
Figure C6-e: Residual – Fitted Plot: Trimmed Data (Reading + Signvar)

Figure C6-f: Cook’s Distance Plot: Trimmed Data (Reading + Signvar)
Table C7-a: Model Validation I: Table of Measured vs. Predicted Grade

<table>
<thead>
<tr>
<th>Measured Grade</th>
<th>Reading</th>
<th>Predicted Grade</th>
<th>Prediction Error</th>
<th>Prediction Sq. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.25</td>
<td>6.00</td>
<td>8.78</td>
<td>-0.47</td>
<td>0.23</td>
</tr>
<tr>
<td>9.25</td>
<td>6.17</td>
<td>9.05</td>
<td>-0.20</td>
<td>0.04</td>
</tr>
<tr>
<td>9.25</td>
<td>6.50</td>
<td>9.58</td>
<td>0.33</td>
<td>0.11</td>
</tr>
<tr>
<td>7.90</td>
<td>5.52</td>
<td>8.01</td>
<td>0.11</td>
<td>0.01</td>
</tr>
<tr>
<td>7.90</td>
<td>5.30</td>
<td>7.65</td>
<td>-0.25</td>
<td>0.06</td>
</tr>
<tr>
<td>7.50</td>
<td>4.89</td>
<td>7.00</td>
<td>-0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>7.50</td>
<td>5.56</td>
<td>8.07</td>
<td>0.57</td>
<td>0.33</td>
</tr>
<tr>
<td>7.50</td>
<td>5.08</td>
<td>7.30</td>
<td>-0.20</td>
<td>0.04</td>
</tr>
<tr>
<td>7.00</td>
<td>5.34</td>
<td>7.72</td>
<td>0.72</td>
<td>0.52</td>
</tr>
<tr>
<td>7.00</td>
<td>5.04</td>
<td>7.24</td>
<td>0.24</td>
<td>0.06</td>
</tr>
<tr>
<td>6.50</td>
<td>5.20</td>
<td>7.49</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>6.50</td>
<td>4.76</td>
<td>6.79</td>
<td>0.29</td>
<td>0.08</td>
</tr>
<tr>
<td>6.50</td>
<td>4.99</td>
<td>7.16</td>
<td>0.66</td>
<td>0.43</td>
</tr>
<tr>
<td>6.00</td>
<td>4.45</td>
<td>6.29</td>
<td>0.29</td>
<td>0.08</td>
</tr>
<tr>
<td>6.00</td>
<td>4.49</td>
<td>6.36</td>
<td>0.36</td>
<td>0.13</td>
</tr>
<tr>
<td>6.00</td>
<td>3.98</td>
<td>5.54</td>
<td>-0.46</td>
<td>0.21</td>
</tr>
<tr>
<td>5.00</td>
<td>3.94</td>
<td>5.47</td>
<td>0.47</td>
<td>0.22</td>
</tr>
<tr>
<td>5.00</td>
<td>3.78</td>
<td>5.22</td>
<td>0.22</td>
<td>0.05</td>
</tr>
<tr>
<td>4.50</td>
<td>3.88</td>
<td>5.38</td>
<td>0.88</td>
<td>0.77</td>
</tr>
<tr>
<td>4.50</td>
<td>3.19</td>
<td>4.27</td>
<td>-0.23</td>
<td>0.05</td>
</tr>
<tr>
<td>4.00</td>
<td>2.64</td>
<td>3.39</td>
<td>-0.61</td>
<td>0.37</td>
</tr>
<tr>
<td>4.00</td>
<td>2.74</td>
<td>3.55</td>
<td>-0.45</td>
<td>0.20</td>
</tr>
<tr>
<td>3.80</td>
<td>3.20</td>
<td>4.29</td>
<td>0.49</td>
<td>0.24</td>
</tr>
<tr>
<td>3.80</td>
<td>2.73</td>
<td>3.53</td>
<td>-0.27</td>
<td>0.07</td>
</tr>
<tr>
<td>3.50</td>
<td>2.30</td>
<td>2.84</td>
<td>-0.66</td>
<td>0.43</td>
</tr>
<tr>
<td>3.50</td>
<td>2.71</td>
<td>3.50</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3.00</td>
<td>2.89</td>
<td>3.79</td>
<td>0.79</td>
<td>0.63</td>
</tr>
<tr>
<td>3.00</td>
<td>2.21</td>
<td>2.70</td>
<td>-0.30</td>
<td>0.09</td>
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Avg. Pred. Error = -0.04

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Figure C7-a: Model Validation 1: Comparison of Measured and Model-Predicted Grade

Comparison of Measured and Predicted Grade

- Measured Grade
- Predicted Grade
Table C7-b: Model Validation II: Table of Measured vs. Predicted Grade

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Avg. Pred. Error = -0.31
Std. Dev. = 0.07
MSRP = -0.31
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VITA

Born at Ngo - Andoni in Rivers State of Nigeria, Dr. Udungs Henry Ikwut-Ukwa followed the family tradition in pursuing higher education. His father, the late Henry Owo Ikwut-Ukwa, was a school teacher and administrator, recognized as a pioneer who encouraged and promoted education in Andoni.

Dr. Ikwut-Ukwa completed high school at Stella Maris College, Port Harcourt and went on to obtain a Bachelor of Science degree in civil engineering (structures) at the University of Ibadan in 1987. He completed his mandatory one year national service in Anambra State, and then spent two years working at the Federal Ministry of Works and Housing in Lagos and Katsina. He then returned to school, attending the University of Oklahoma, Norman where he obtained a Master of Science degree in civil engineering (environmental) in 1994. Thereafter he enrolled at the Georgia Institute of Technology, Atlanta where he obtained a Master of Science degree in civil engineering (transportation) in 1999, and a Doctor of Philosophy in civil engineering and public policy in 2001.

Currently Dr. Ikwut-Ukwa is a consultant with the engineering consulting firm - Parsons Transportation Group, Inc. His diverse background in civil engineering covers structures, geotechnical, transportation, and environmental fields. His research interests are focused on the planning, design and management of transportation infrastructure, and the environmental impacts of transportation activities, specifically in the area of vehicle emissions and air quality modeling.