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Developing Driving Support Systems to Mitigate Behavioral Risk Patterns Among Teen Drivers

Final Report

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16. Abstract (Limit: 200 words)

Teen drivers have a higher fatality risk than any other drivers on the road. Despite teenagers making up only 4.6% of all licensed drivers, they are involved in 13% of all fatal crashes. Approximately six thousand teenagers are killed in motor vehicle crashes every year, and this number has remained constant for the over a decade; making automobile crashes the leading cause of death among this age group. As a result, new approaches to mitigate teen fatalities must be investigated.

This paper focuses on potential of in-vehicle technology to monitor and correct unsafe teen driver behavior. In order to determine what types of technologies would be most beneficial, common factors that play a role in teen driver fatalities are first identified. We then describe the mechanisms that lead to these kinds of behavior, and methods in which each behavior could be corrected are described – by means of forcing, feedback, or reporting functions. Examples of in-vehicle technologies are then given for each function. Finally, a recommendation is made for a system that uses a combination of the triad of functions to specifically address the common factors that lead to teen driver fatalities.

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Acronyms/Abbreviations

AASHTO: American Association of State Highway and Transportation Officials
ADAS: Advanced Driver Assistance System
APSO: ADAS Product Set One
AT: Attention
BAC: Blood Alcohol Concentration
BrAC: Breath Alcohol Concentration
CAD: Computer Aided Drafting
CAN: Controller Area Network
CDC: Center for Disease Control
CDR: Crash Data Retrieval
CSAH: County State Aide Highway
CSW: Curve Speed Warning
DBMS: Database Management System
DGPS: Differential GPS
DLC: Data Link Connector
DMI: Distance Measuring Instrument
DMS: Dynamic Message Signs
DOT: Department of Transportation
DPS: Department of Public Safety
DR: Dead Reckoning
DUI: Driving Under the Influence
ECU: Engine Control Unit
EDMap: Enhanced Digital Map
EDR: Event Data Recorder
FARS: Fatality Analysis Reporting System
FHWA: Federal Highway Administration
FMVSS: Federal Motor Vehicle Safety Standards
GDF: Geographic Data Files
GDL: Graduated Drivers Licensing
GIS: Geographic Information Service
GPRS: General Packet Radio Service
GPS: Global Positioning System
HIPL: Heading Improved Point to Link
HUD: Heads-up Display
IIHS: Insurance Institute for Highway Safety
IMU: Inertial Measurement Unit
ISA: Intelligent Speed Adaptation
ITS: Intelligent Transportation System
IV Lab: Intelligent Vehicles Lab
LRS: Linear Reference System
MM: Map Matching
Mn/DOT: Minnesota Department of Traffic Safety
MUTCD: Manual on Uniform Traffic Control Devices
MVMT: Million Vehicle Miles Traveled

NCHRP: National Cooperative Highway Research Program
NHTS: National Household Travel Survey
NHTSA: National Highway Traffic Safety Administration
NMAS: National Map Accuracy Standard
NOPUS: National Occupant Protection Use Survey
NSDUH: National Surveys on Drug Use and Health
OBD-II: On Board Diagnostics, 2nd Generation
OTS: Office of Traffic Safety
PDA: Personal Digital Assistant
PPP: Point-to-Point Protocol
RDM: Road Design Manual
RPM: Revolutions per Minute
RWIS: Road Weather Information Service
SAE: Society of Automotive Engineers
SAMHSA: Substance Abuse and Mental Health Services Administration
SMS: Short Message Service
SSI: Surface Systems, Inc
TCD: Traffic Control Device
TDC: Trip Data Calculator
TDSS: Teen Driver Support System
TEM: Traffic Engineering Manual
TIS: Transportation Information Service
TP: Throttle Position
TRB: Transportation Research Board
UMTRI: University of Michigan Transportation Research Institute
USDOT: United States Department of Transportation
USGS: U.S. Geological Survey
UTM: Universal Transverse Mercator
VSL: Variable Speed Limit
WAAS: Wide Area Augmentation System

Symbols

d_0 = distance (in miles) of vehicle along the current roadway
d_P = perpendicular distance between vehicle road link
r = vector between vehicle and previous point on road link
v = vector passing through vehicle position and normal to the road link
(x_0,y_0) = coordinates of vehicle's current position
(x_1,y_1) = coordinates of previous point on road link
(x_2,y_2) = coordinates of next point on road link
a_1 = linear distance along the road link of the vehicle from the previous point
d_1 = distance (in miles) of previous point along the current roadway
V_{curve} = advisory curve speed
R_{curve} = radius of curve
e = superelevation of curve
f = friction factor
V = current speed of vehicle
θ_1 = angular orientation of the roadway at the start of the curve
θ_2 = angular orientation of the roadway at the midpoint of the curve
d = direction of travel along the roadway (increasing = +1, decreasing = -1)
D_{react} = reaction distance
t_{react} = reaction time, 2.5 seconds
D_{brake} = braking distance
a = deceleration rate, 8.1 m/s^2
TP = actual throttle position
TP_0 = calculated throttle position threshold at 0 mph
TP_{70} = calculated throttle position threshold at 70 mph

Executive Summary

Based on statistics from the Center for Disease Control (2003), motor vehicle deaths are the leading cause of teenage fatalities. In 2004, while teenage drivers made up only 4.7% of all licensed drivers, they accounted for 11.3% of all passenger vehicle deaths (Federal Highway Administration [FHWA], 2005; Insurance Institute for Highway Safety [IIHS], 2004). A review of fatal crash statistics shows that, among teenage drivers, speeding, alcohol impairment, and low seatbelt use all play a dominant role in causing crashes and a higher level of fatalities. Statistics from 2004 Fatality Analysis Reporting System (FARS) data shows that speeding is cited in 44% of fatalities of the 16 to 19-year-old drivers, which is higher than any other age group. In 2004, 22% of the 16 to 19-year-old drivers killed had a Blood Alcohol Concentration (BAC) of 0.08 grams per deciliter (g/dL) or higher (NHTSA, 2004a). Although seatbelt use is not a contributing factor in the *cause* of a fatal crash, low seatbelt use rates clearly contribute to the high level of fatalities associated with teen crashes. McCartt and Northrup (2004) show that from 1995-2000 nationwide seatbelt use was lowest among teenagers (16 to 19 years old) with only 36% among fatally injured teen drivers, and 23% among fatally injured passengers. These factors are also reoccurring issues that show up in observational studies on the risk behaviors of teenagers. These behaviors are significant not only because they are so common, but also because there is potential for these factors to be addressed by interventional methods.

To make a significant impact in the reduction of teen driver fatalities, new approaches must be considered. One approach to reduce the incidence of teenage driver crashes and fatalities is through the use of in-vehicle intelligent driver support technology. This report describes the development of a Teen Driver Support System (TDSS), which combines several such technologies to address the primary contributing factors associated with the majority of teen fatal crashes (speeding, low seatbelt use, and alcohol impairment). The TDSS described here also offers an opportunity to address the issue of inexperience through enforcement of certain Graduated Drivers Licensing (GDL) provisions.

The TDSS system is implemented using a combination of forcing, feedback, and reporting functions. Thus, the goal is to incorporate technologies that integrate these functions. A forcing function works by forcing actions in a safe sequence prior to vehicle operation, or prohibits vehicle operation while an undesired behavior persists. In the TDSS, forcing functions take the form of ignition interlocks to enforce seatbelt compliance and sober driving. The feedback function provides real time warnings about illegal or unsafe speeds (such as advisory curve speeds and/or dynamic speed thresholds based on weather conditions). This function primarily works by augmenting driver performance through feedback used as part of the learning process. The reporting function gives parents or other authorities in the social environment of the teen driver insight into how the teen is driving through real-time and off-line records. Notably, the use of the reporting function provides a tool that facilitates consequences for risky behaviors and rewards safe behaviors.

A review of past and present commercially available teen focused in-vehicle systems has identified a number of deficiencies; the systems are too passive and do not incorporate the best possible technological solutions. Ultimately, these devices are monitoring systems. By classifying them according to the function methods of forcing, feedback, and reporting, none of these devices offer a forcing function. A limited number of systems offer a feedback function, but most devices are primarily reporting-type systems. These devices range in cost from about $200 to more than $1,000, with the more advanced devices having on-board GPS to monitor and record the location of the driver. Systems offering GPS-based position monitoring are only used to track the location of the teen driver; they do not correlate vehicle position to local speed limits or recommend speeds. In addition, no device requires seatbelt use or sobriety prior to vehicle operation.

The enabling technologies of the TDSS described in this report take advantage of past, existing, emerging, and new technologies. The TDSS borrows ideas from Intelligent Speed Adaptation (ISA), seatbelt and alcohol interlock systems, biometric fingerprint identification, SMS messaging, and current teen driver monitoring systems. However, the TDSS is the first time that all of these technologies have been combined to form a single support system that focuses specifically on teen safety issues. TDSS is built around an in-vehicle computer that serves as a hub for its components. The ISA component of the TDSS is based on Mn/DOT's publicly available basemap and a speed limit database. It also includes warnings based on advisory curve speed data from county curve speed survey sheets and real-time weather data from Mn/DOT's Road Weather Information Service (RWIS). The driver identification component makes use of a biometric fingerprint reader to identify a driver and parent. This feature provides the means for the parent to opt out of the system and maintain his or her privacy if desired and enables the enforcement of GDL restrictions. The real-time reporting system makes use of the GPRS modem that is also used to download weather information from RWIS. The modem is capable of sending reports to a specified cellular phone number or to a specified e-mail address using a cellular provider's Short Message Service (SMS). The seatbelt ignition interlock prevents the vehicle from being started if the driver's seatbelt is not engaged. The alcohol ignition interlock is being considered as an optional component; it was not installed on the TDSS demonstration unit because of cost, but is currently available from a number of manufacturers. In order to relay information to the driver, an audio interface was developed. The purpose of the audio interface was to provide the driver with contextual-based information about his or her current driving behavior, the current driving environment, and/or general system information.

A review of literature on the subject of in-vehicle technology and teen drivers shows that aside from focus groups there have been no evaluations thus far because research on driver assistive technology to date has not focused on teenagers specifically. This is alarming given their high risk of crash and injury when behind the wheel.

- In a 2003 study by an Australian group (Young, Regan, Mitsopoulus, & Haworth), a system was proposed with similar technology to the TDSS system. Focus groups were held with 58 urban and rural young drivers between the ages of 17 and 25 to discuss the perceived acceptability and price they would pay for several Intelligent Transportation System (ITS) devices. As a result of the study, the proposed system would include ISA, the alcohol interlock system, and the seatbelt reminder system.

- In a Transportation Research Board (TRB) report by the Committee for the Safety Belt Technology Study (2004), NHTSA conducted focus groups among several different age categories to evaluate the perceived effectiveness and acceptability of seatbelt reminder systems, and the use of interlocks. As a result, the committee recommends that use of interlock (both for seatbelt use and alcohol use) technologies should be reserved for high-risk groups such as teen drivers.

- A comprehensive review of literature was conducted by NHTSA (2004b) to identify programs, interventions, and strategies to effectively increase seatbelt use. In addition to recommending primary seatbelt laws, the report also recommends adding seatbelt requirements to GDL programs, and using technology such as seatbelt reminders and interlocks.

This technology also presents an opportunity to:

- Integrate technology within a safety program such as GDL to gain synergistic safety benefits that target the specific risk patterns of teen drivers. A TDSS allows GDL systems to incorporate new requirements (e.g. seatbelt use) and provides a way of monitoring compliance.

- Prompt parents to become actively involved in the training of their teen drivers through the use of the TDSS reporting. Parental involvement is an integral component to making successful improvements in teen driving behavior.

- Reduce insurance premiums among those drivers using the device who demonstrate safer driving habits.

Human factors research is needed to develop an effective and acceptable form of TDSS. Critical research issues include the type of feedback used to interface with drivers and parents, and the threshold levels used to trigger feedback.

1. Introduction

1.1 Motivation – Teen Crash Statistics

Although it is well known that the crash risk of teenagers is especially high, what is most disturbing is that teenagers are those most likely to be fatally injured when involved in a crash. An analysis of crash data by Williams (2003) showed that teenage drivers have the highest risk of crash involvement among any age group, with risk particularly high right after licensure. As a result of their propensity to crash, teenagers are overrepresented in fatal crash statistics. On the national level in 2004, teenagers aged 16 to 19 years old made up only 4.7% of all licensed drivers, yet they accounted for 13% of all passenger vehicle deaths (Federal Highway Administration [FHWA], 2005; Insurance Institute for Highway Safety [IIHS], 2004). Motor vehicle deaths are the leading cause of death among this age group. Based on 2003 statistics from the Center for Disease Control (CDC), motor vehicle traffic crashes accounted for over a quarter (4,733 out of 12,198) of all deaths among 16 to 19 year olds. Clearly motor vehicle crashes are at epidemic proportions among this population group.

In Minnesota, similar trends among teenagers occur. As shown in Table 1-1, teenagers between the ages of 16 and 19 make up 6.6% of licensed drivers, and are overrepresented at 13.4% of motor vehicle fatalities (Minnesota Office of Traffic Safety [OTS], 2005). In 2004, there were 567 persons killed in motor vehicle crashes; 76 of those were between the ages of 16 and 19. Looking at Figure 1-1, the fatality rate (in terms of 100,000 licensed drivers) among teenagers is higher than any other age group; teenagers aged 16-19 years old have fatality rate of nearly 30 deaths per 100,000 licensed drivers.

Figure 1-1: Motor vehicle fatalities per 100,000 licensed drivers by age, Minnesota 2004 (Minnesota OTS, 2005)

Table 1-1: Data used in Figure 1-1

Age	Fatalities	Fatalities as % of Total	Licensed Drivers	Licensed Drivers as % of Total	Rate (Fatalities/100,000 licensed drivers)
16	15	2.6	55812	1.4	26.9
17	20	3.5	61286	1.6	32.6
18	21	3.7	66397	1.7	31.6
19	20	3.5	71026	1.8	28.2
16-19	76	13.4	254521	6.6	29.9
20-24	71	12.5	361589	9.4	19.6
25-29	42	7.4	339712	8.8	12.4
30-59	214	37.7	2106468	54.7	10.2
60-69	46	8.1	366168	9.5	12.6
70+	83	14.6	391760	10.2	21.2
Total	567		3851865		

For an analysis of the relative risk of teen drivers compared to older drivers, it is most appropriate to look at statistics for license-aged teenagers who were drivers of passenger vehicles. Tables 1-1 & 1-2 and Figures 1-2 & 1-3 compare driver fatality rates of 16 to 19 year old driver to drivers of other age groups in terms of licensed drivers and miles traveled on the national level. Age categories are similarly grouped to the above figure so that the relative risk of teenagers can be compared to slightly older drivers (drivers in their 20's), middle aged drivers (drivers in the 30 to 59 year old group), and older driver (drivers over 60). Mileage information was based on data gathered by IIHS from the 2001 National Household Travel Survey (NHTS). Driver fatality data came from the U.S. Department of Transportation's (USDOT) Fatality Analysis Reporting System (FARS) for the year 2004. Licensing data was collected from the FHWA publication on 2004 Highway Statistics (FHWA, 2005).

Figure 1-2 shows that in terms of driver deaths per population of licensed drivers, teenagers are clearly at the highest risk. Looking at Table 1-2, there were 2,483 teenage drivers between the ages of 16 and 19 killed in passenger vehicles in 2004. In terms of licensed drivers for this age group, that is a fatality rate of 26.7 driver deaths per 100,000 licensed drivers. Looking at 16 year old drivers, the rate is even higher at 31.9. The next highest rate of 18.9 driver deaths per 100,000 licensed drivers was among the 20 to 24 year old group. By comparison, the rate among persons aged 30 to 59 was 8.2 driver deaths per 100,000 licensed drivers. That means that the fatality risk of the 16 to 19 group is over 3 times greater than the risk of the 30 to 59 year old group in terms of licensed drivers.

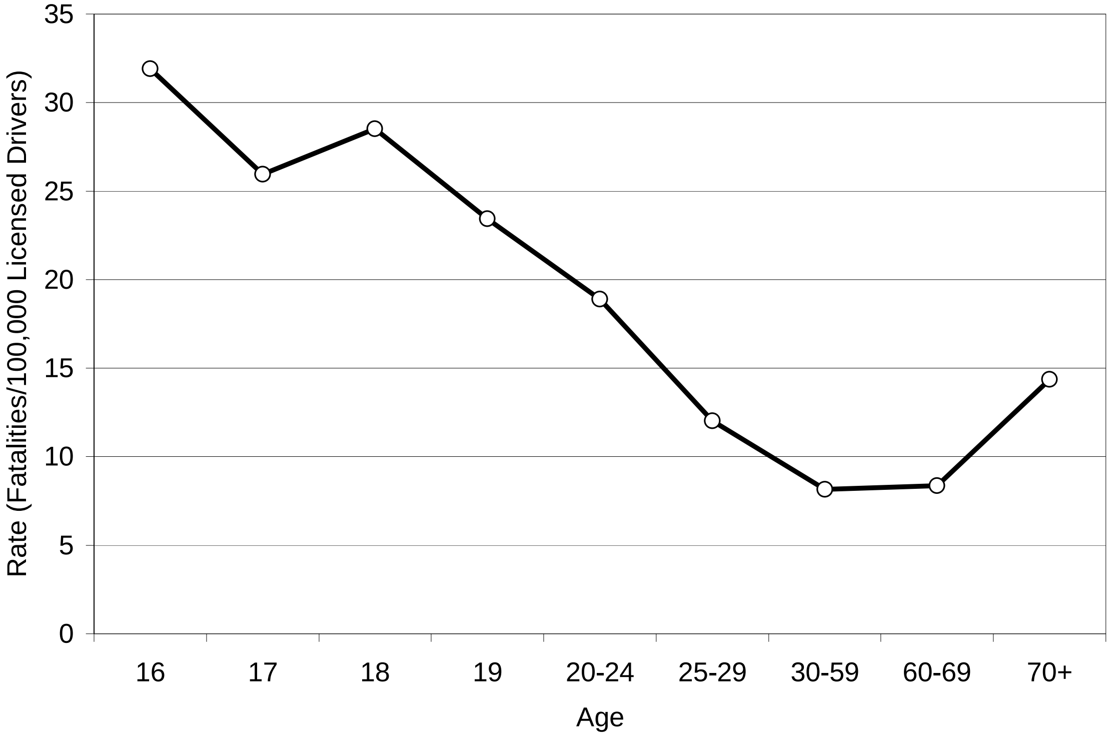

Figure 1-2: Driver fatalities in passenger vehicles per 100,000 licensed drivers by age (FARS 2004; FHWA 2004)

Table 1-2: Data used in Figure 1-2

Driver Age	Driver Fatalities	Fatalities as % of Total	Licensed Drivers	Licensed Drivers as % of Total	Rate (Fatalities/100,000 licensed drivers)
16	399	1.8	1,250,800	0.6	31.9
17	566	2.6	2,181,110	1.1	26.0
18	789	3.6	2,766,621	1.4	28.5
19	729	3.3	3,109,625	1.6	23.4
16-19	2,483	11.3	9,308,156	4.7	26.7
20-24	3,194	14.6	16,899,142	8.5	18.9
25-29	2,091	9.6	17,381,258	8.7	12.0
30-59	9,335	42.6	114,412,931	57.5	8.2
60-69	1,749	8.0	20,896,002	10.5	8.4
70+	2,869	13.1	19,966,493	10.0	14.4
Total	21,895		198,888,912		

Figure 1-3 shows that in terms of exposure on a per mile basis, the numbers reinforce the fact that the teenage group of drivers is at the highest risk. Looking at Table 1-3, there were 3.0 deaths per 100 Million Vehicle Miles Traveled (MVMT) among 16 to 19 year olds. The next highest rate was 1.9 deaths per 100 MVMT among 20 to 24 year olds. Compare that with a rate of 0.7 deaths per 100 MVMT for 30 to 59 year olds. The fatality risk of the 16 to 19 group is over 4 times greater than the 30 to 59 year old group in terms of miles traveled.

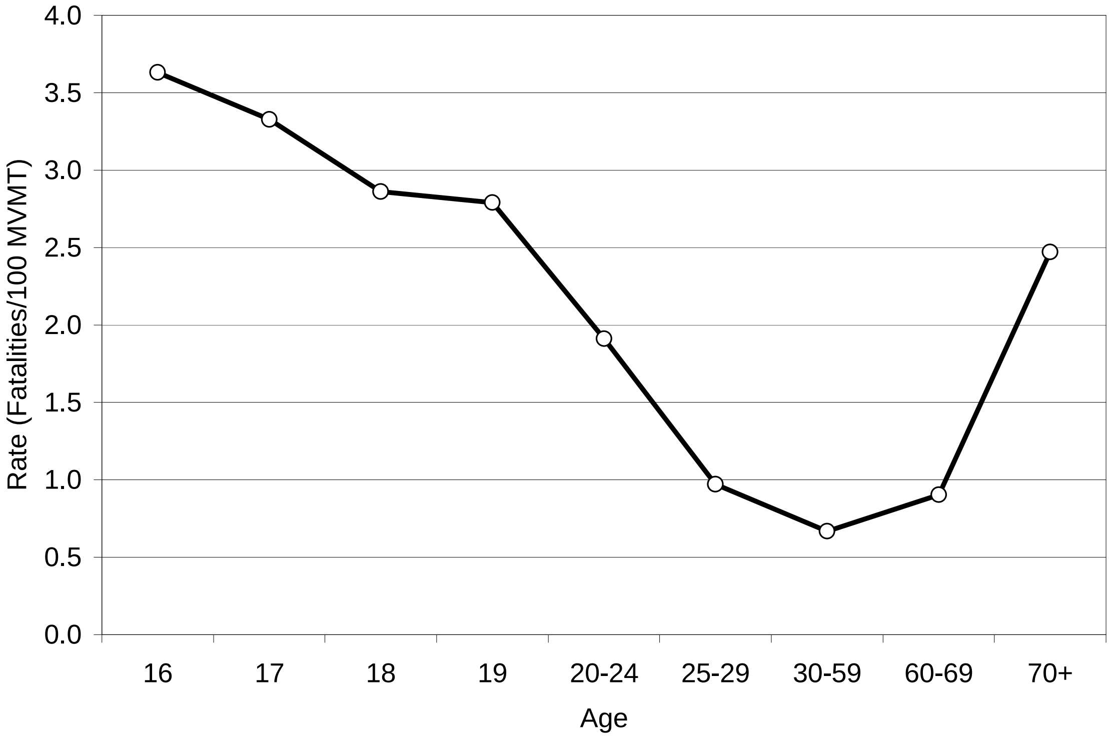

Figure 1-3: Driver fatalities in passenger vehicles per 100 MVMT by age (FARS 2004; NHTS 2001)

Table 1-3: Data used in Figure 1-3

Driver Age	Driver Fatalities	Fatalities as % of Total	Miles Traveled	Miles Traveled as % of Total*	Rate (Fatalities/100 MVMT)
16	399	1.8	10,991,775,116	0.5	3.6
17	566	2.6	17,007,229,957	0.8	3.3
18	789	3.6	27,575,876,114	1.3	2.9
19	729	3.3	26,116,988,928	1.2	2.8
16-19	2,483	11.3	81,691,870,115	3.8	3.0
20-24	3,194	14.6	167,139,739,780	7.7	1.9
25-29	2,091	9.6	215,143,526,035	9.9	1.0
30-59	9,335	42.6	1,396,858,272,119	64.4	0.7
60-69	1,749	8.0	193,593,030,635	8.9	0.9
70+	2,869	13.1	116,084,984,569	5.3	2.5
Total	21,895		2,170,511,423,253		

*Total miles traveled excludes drivers 15 and under.

These numbers for teenage drivers are clearly unacceptable. Therefore, a new approach to reduce teen fatalities that can make a significant impact must be considered. As suggested in this document, a possible approach to reduce the incidence of teenage driver crashes and fatalities is through the use of in-vehicle technology to monitor and correct unsafe teen driver behavior. Through advancements in Intelligent Transportation System (ITS) technologies and other safety technologies, we are now presented with an opportunity to further develop and implement such technology so that it may benefit the young driving population.

This document discusses the development of such technologies and a method for combining them to form a Teen Driver Support System (TDSS). The TDSS system described here was developed based on a notion that the crash fatalities of teenage drivers could be reduced by addressing common risk patterns/behaviors that play a role in a majority of teen driver fatalities. As one can imagine, there are many such risk behaviors. However, within the limits of developing technology, it is possible that some of the most common risk behaviors can still be addressed, and thus lead to an overall reduction in teen driver deaths. The technology used, common risk factors, and methods by which the TDSS addresses these factors are discussed in detail throughout this document.

As a result of the high fatality rate among young drivers, much attention has also been given to the development of teen crash countermeasures through Graduated Driver Licensing (GDL). GDL programs have become an increasingly popular method to address young drivers' lack of experience. Specifically, GDL programs aim to reduce the exposure of a young inexperienced driver to high risk driving situations, such as at night driving or driving with other teenage passengers. Therefore, the driver can gain experience through low risk driving before reaching the stage of full licensure. However, GDL systems tend to deal with the risk situations, and not the behaviors that lead to many of the crashes that result in teen driver fatalities. Using in-vehicle technology it may be possible to deal with both. This technology presents an opportunity to specifically address some of these behaviors, and such systems can also be directly incorporated into current GDL programs thus providing new tools to maximize its effectiveness.

1.2 Crash Risk Factors

From a statistical standpoint, it is clear that teen drivers are at a much higher risk than drivers of other age groups of being involved in a crash and also being fatally injured. From crash statistics it is also possible to determine the risk behaviors that account for a disproportionate number of fatalities. An evaluation of crash statistics and prior research outlines some of the risk behaviors that may explain why young drivers are overrepresented in traffic fatalities, and provides insight into what types of technology could help address the teen driver problem.

Among teenage drivers, speeding, alcohol impairment, and low seatbelt use are responsible for a significant number of crash fatalities. These factors are often reoccurring issues that also show up in observational studies on the risk behaviors of teenagers. This would lead one to believe that there is room for additional countermeasures to prevent these behaviors through the use of in-vehicle technology. These behaviors are discussed here not only because they are so common, but also because there is potential for these factors to be addressed by interventional methods.

1.2.1 Speeding

Speeding contributes to an overwhelming percentage of fatal crashes among teenagers. Although speeding is not a unique problem associated only with teenagers, the magnitude of its involvement for teenagers is unique. Speeding plays an overwhelming role in all fatal crash types among teenagers. Data from Minnesota shows that in 2002, speeding was the primary causal factor in 30% of all teen (16-19 year old) driver fatal crashes (This data was analyzed from a data query request provided by Alan Rodgers with the Minnesota Office of Traffic Safety).

Figure 1-4 is based on statistics gathered from FARS for the year 2004. This figure shows the percentage of driver fatalities in passenger vehicles in which driving too fast for conditions, or in excess of the posted maximum was cited as a driver related causal factor by police officers. The figure is broken down by age categories for comparison.

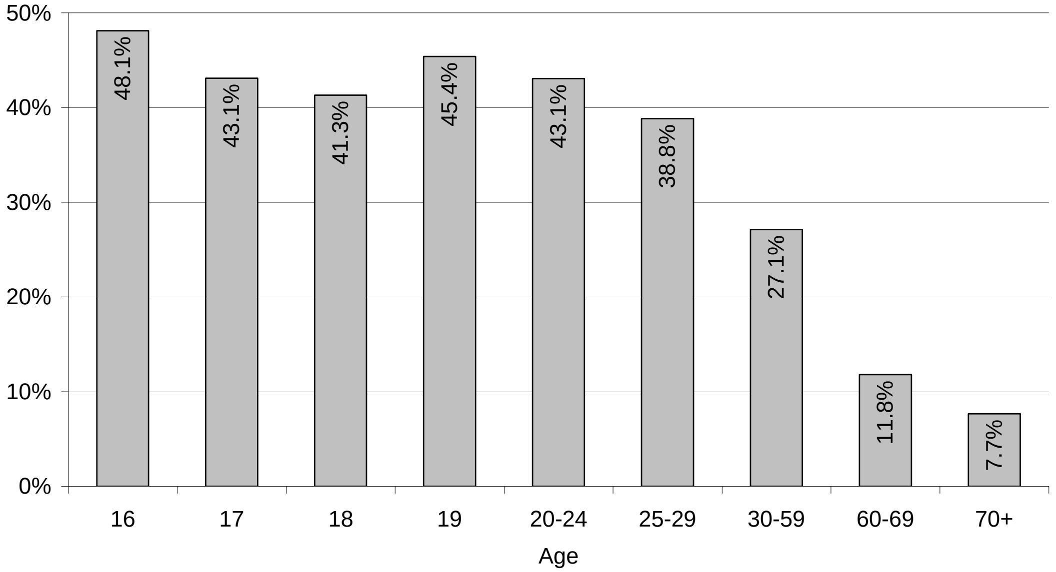

Figure 1-4: Percent of drivers fatally injured in passenger vehicles that were driving too fast for conditions or in excess of posted maximum by age
(FARS 2004)

From Figure 1-4, it is clear that, on the national level, speeding is more commonly cited in teen driver fatalities than the older age groups. Driving too fast for conditions or in excess of the posted maximum was cited in over 48% of 16 year old driver fatalities in 2004. When looking at the 16 to 19 year old drivers as a group, speeding is cited in 44% of fatalities, which is higher than any other age group. Only 18 year old drivers had a slightly lower percentage than the 20 to 24 year old group. Speeding is also commonly cited among drivers in their 20's, but for the older age groups, the percentage of fatalities in which driving too fast for conditions or in excess of the posted maximum continues to decline. From this trend, it is clear that speeding is more likely to be a factor the younger the age group.

Results from observational studies and reports of fatal and nonfatal crashes agree that teen drivers are likely to speed. Williams, Preusser, and Ferguson (1998) conducted an evaluation of nighttime fatal crashes among 16 year old drivers in California. Their study included police reports and newspaper reports between 1989 and 1994. They found 16 year old fatalities are more often in single vehicle crashes that involve speeding, higher occupancy rates, and commonly result from driver error. Gonzales, Dickinson, DiGuiseppi, and Lowenstein (2005) compared fatal crashes among 16 year old drivers to an age group of 25 to 49 year olds in Colorado between 1995 and 2001. They concluded that speeding and seatbelt nonuse are more likely cited in fatal crashes among novice driver as compared to older drivers. McKnight and McKnight (2003) conducted a study of 2000 nonfatal crashes among 16 to 19 year old drivers in California and Maryland and found speeding to be one of the leading causes of crashes. In a study conducted by Boyce and Geller (2003), an instrumented vehicle was used to record behavioral data among drivers aged 18 to 82. They reported that younger drivers (18 to 25) were more likely to speed than older drivers, and overall, young drivers are more likely to drive at risk.

1.2.2 Alcohol Use

Alcohol also continues to be an issue among teen drivers. In 2004, 22% of the 16-19 year old drivers killed had a Blood Alcohol Concentration (BAC) of 0.08 grams per deciliter (g/dL) or higher (National Highway Traffic Safety Administration [NHTSA], 2004a). Although alcohol involvement is more common among older drivers, alcohol may have a greater impact on young drivers. Zador, Krawchuck, and Voas (2000) found that drivers aged 16-20 with a BAC of 0.08-0.10 g/dL are more likely (*52* times for males; 15 times for females) to be killed in a single-vehicle crash than a sober teen driver. Compare this to drivers aged 35 and older who are 11 times more likely with a BAC of 0.08-0.10 g/dL.

Despite the fact that teen drivers are subject to zero tolerance laws, many teenagers report that they have driven after consuming alcohol. In the 2002 and 2003 U.S. National Surveys on Drug Use and Health (NSDUH), 17% of 16 to 20 year olds had reported that they had driven under the influence of alcohol in the past year (Substance Abuse and Mental Health Services Administration [SAMHSA], 2004). In 2002, a survey of 400 drivers in California between the ages of 19 and 25 showed that 88% of respondents felt that obtaining alcohol was easy for an underage person, and 17% reported that they had driven after drinking too much to safely drive (University of California Traffic Safety Center, 2003).

1.2.3 Seatbelt Use

Although seatbelt use is not a contributing factor in the cause of a fatal crash, low seatbelt use rates clearly contribute to the high level of fatalities associated with teen crashes. McCartt and Northrup (2004) show that from 1995-2000 nationwide seatbelt use was lowest among teenagers (16 to 19 years old) with only 36% among fatally injured teen drivers, and 23% among fatally injured passengers. When looking at both drivers and passengers, NHTSA reports that in 2004 only 36% of passenger vehicle occupants killed between 16 and 20 years old were restrained (NHTSA, 2004b). Results from the 2005 National Occupant Protection Use Survey (NOPUS) observational study shows that seatbelt use among the 16 to 24 year age category is lowest at 78%, while the national average is at 82% (Glassbrenner, 2005a). An observational study by Williams, McCartt, and Geary (2003) has also shown that teenagers are less likely to wear their seatbelts than adults, and teenage passengers are even less likely to wear their seatbelt when the driver is not buckled. This means teenagers, who are most likely to be involved in a crash, are also the least likely to wear their seatbelt. Add alcohol, and teen drivers are even less likely to wear their seatbelt (McCartt & Northrup, 2004; Williams & Shabanova, 2002). These low use rates are alarming considering the elevated crash risk of teen drivers.

Once of the most significant predictors of whether or not a teen driver is belted in a crash is if the state has a primary seatbelt law. A primary seatbelt law gives an officer the right to pull someone for a seatbelt violation. McCartt and Shabanova (2002) showed that 47% of fatally injured teen drivers were buckled in states with a primary law, compared to 30% in states with a secondary law. Better seatbelt enforcement, such as a primary seatbelts law, has proven to be an effective strategy to increase seatbelt use (National Cooperative Highway Research Program [NCHRP], 2004). Although primary seatbelt laws are effective, too many states have still not passed such laws and are clearly resistant to such legislation. Therefore, to reduce fatalities among teenagers it is important to also consider the use of other means that have potential for effectiveness. A comprehensive review of literature was conducted by NHTSA (2004c) to identify programs, interventions, and strategies to effectively increase seatbelt use. In addition to recommending primary seatbelt laws, the report also recommends adding seatbelt requirements to GDL programs, and using technology such as seatbelt reminders and interlocks. The report concludes that the use of a combination of such strategies has the greatest potential to increase seatbelt use.

1.2.4 Inexperience

As previously mentioned, the issue of inexperience is being dealt with through enforcement of GDL provisions. Teen drivers' lack of experience is another factor that often contributes to their elevated risk. Teen drivers are most likely to be involved in a crash in the time period immediately after licensure. Mayhew, Simpson, and Pak (2003) show that young drivers are at the highest risk up to six months after licensure, after which time crash rates decline significantly. This suggests that overconfidence and lack of skill often leads to high crash rates of beginning teen drivers. McCartt, Shabanova, and Leaf (2003) showed that in terms of mileage, young drivers are at the highest risk in the first 500 miles driven. Although inexperience is a factor that affects a beginning driver no matter their age, it generally has a greater affect on younger novice drivers (Maycock, Lockwood, & Lester, 1991).

1.3 Project Goals, Objectives, and Constraints

The primary goal of this project was the development of a TDSS that could be used to address common risk factors (speeding, lack of seatbelt use, alcohol, and inexperience) that play a role in a majority of teen driver fatalities. In order to develop the TDSS, the first task was the identification of the common risk factors in a majority of teen driver fatal crashes. These factors are listed above in section 1.2, and supporting information for each factor is given. These factors were selected based on their significance, perceived importance, and their ability to be addressed by the TDSS.

In addition to addressing the common risk factors, there were also a number of other objectives that needed to be met by the TDSS. One objective was the ability of the system to log driver data and organize that data into a driver performance record. Another objective was to incorporate within the TDSS the ability to track and enforce certain recommended GDL restrictions. The final objective, which ties in with the GDL component, is the ability of the system to protect parental privacy by disabling the TDSS for the parent driver if he or she so chooses.

There were also a number of constraints that were initially imposed on the project, which influenced how the system was developed. The first constraint was to keep the overall cost of the system to a minimum. The second constraint was the system was to be as minimally invasive to the vehicle as possible - meaning that the system should not require any significant or permanent alteration of the vehicle, and for the most part should simply "plug in" to the vehicle. Making the system minimally invasive allows it to be moved from one vehicle to another. Another constraint was to include a driver interface so the technology could be easily demonstrable and understandable to the casual observer. The final constraint was to make the system as small and compact as possible so that it could easily fit within a vehicle without limiting passenger space.

Once the causes of fatal teen crashes were known, and the constraints had been identified, the next task was to identify individual technologies that could be used to specifically address these common and preventable causal factors. To select these technologies, a thorough investigation of historical and current in-vehicle safety technologies was explored. In the end, the TDSS became a combination of borrowed ideas from past technologies, along with the development of "new" technology to suit the specific needs of a teen-focused system.

As a result, the TDSS device developed for this project met the goals, objectives, and constraints initially created. The TDSS used a combination of technologies that were used to mitigate the above factors responsible for teen driver fatal crashes. Intervention was implemented in the form of methods to force behavior, modify behavior using feedback, and report driver behavior for later review. To address the speeding issues, a primary component that was developed is a feedback function to provide real time tutoring and warnings about illegal or unsafe speeds based on local speed limits, road geometry, and weather conditions. Forcing functions take the form of ignition interlocks to enforce seatbelt compliance and sober driving. The reporting function promotes parental involvement by providing real-time and off-line records for review and enforcement of driver performance. Other components include functions to limit excessive acceleration and a means to identify the driver and parent for logging of GDL regulations. These features provide direct and indirect solutions for the issue of driver inexperience. Details of how these components operate and how they were implemented are described throughout this thesis.

It should also be noted that the final system created for this project was to be developed for the purposes of demonstration and research only. Although this project could eventually lead to the development of a commercial product, making a commercial product was not a primary goal of the project. These constraints served as guidelines to create a research-based system and to lay the groundwork for future iterations of the TDSS, from which we can learn what does or does not work.

1.4 Document Layout

The following chapters of this document discuss the many aspects of the TDSS, with specific detail given to the methodology used, and the development of the technology that made this project possible. Chapter 2 is a background discussion of technologies and research projects that relate to this project. Chapter 3 discusses the methods by which the technology interacts with the driver to prevent risky behavior. Chapters 4 through 7 discuss the technology used in the system, how it was developed, and how it was implemented. Chapters 9 presents a validation experiment used to test the performance of certain components on the TDSS, and the results of these experiments. Finally, Chapters 10 and 11 discuss the role of a TDSS in graduated licensing programs, future implications of this technology, secondary benefits, and how it could be best used to increase young driver safety, and ultimately save lives.

2. Related Work

In-vehicle technologies and safety related systems are a growing area of research and product development. While this project focused on the use of in-vehicle safety technologies specifically applied to beginning teen drivers, the use of in-vehicle safety technologies has been developing and growing for decades. Technologies such as airbags, seatbelt reminders/buzzers, ABS braking systems, stability control systems, anti-roll systems, and many others have become common factory options from a number of automobile manufacturers, and in some cases are even required (for the case of airbags and seatbelt reminders) by NHTSA in all new vehicles. There is also a growing market for third party or aftermarket safety systems, and there have been further advancements in the development of ITS related technologies. Products such as alcohol interlocks and driver performance monitoring devices can be installed by the consumer to address specific traffic safety issues and/or improve driver behavior.

While these products address many of the safety issues involved in the often complicated and risky task of operating a motor vehicle, there still remains much room for improvement and further development of new technologies. Sadly, there has been very little research put into the development and evaluation of technologies that address the common risk factors often associated with young drivers. For the case of young drivers, we have an opportunity to introduce safety technologies at the time of licensure. The goal of these technologies should be to mitigate the specific crash risks common to teen drivers, and to develop good driving habits early on, so that once the drivers graduate to full licensure the good driving behaviors remain. As a result, the drivers may become increasingly safe, thus reducing the number of crash fatalities afflicting this population.

2.1 Literature Review

Over the years, there have been numerous evaluations of ITS technologies. Since this project focuses on the use of a few select technologies in the ITS category (Intelligent Speed Adaptation, Curve Speed Warning, Variable Speed Limit, seatbelt interlock, alcohol interlock), the following summaries only pertain to those technologies which were selected for use as part of the TDSS, address the safety issues that were discussed in the previous section, or use relevant technologies similar to the TDSS.

2.1.1 Intelligent Speed Adaptation

There have been a number of evaluations of the speed limiting and alerting technology known as Intelligent Speed Adaptation (ISA). ISA is currently under extensive research in Europe (United Kingdom, Sweden, Netherlands, Denmark, Finland), and has also been evaluated in other countries overseas such as Australia and Japan. Very little research to date involving ISA has taken place in the United States. Details of each study are not described here because they are beyond the scope of this report, but a complete summary of research on this topic and some commercial ISA systems is given in a recent (2006) paper published by the University of Leeds (Jamson, Carsten, Chorlton, & Fowkes, 2006). The summaries listed below were included because they were determined to be relevant to this project.

A relevant project on the topic of ISA and rewarding safe driving behavior was recently conducted in the Netherlands (Undine, 2006). In this project, called the Belonitor trial (a combination of the Dutch word *belonen* (for rewarding), and monitoring), 62 cars were equipped with technology to monitor the speed of the driver with respect the speed limit and the following distance of their car to the vehicle in front of them. The system provided real-time continuous feedback to the driver in the form of a visual display containing symbols for speed and following distance. Although there have been many studies involving ISA and following distance, the unique aspect of this project was the method by which the drivers' behavior were corrected. Instead of being punished for poor behavior, the drivers were rewarded for safe driving behavior. Reward points for safe driving were given a monetary value, so the safer the driver, the more money they would earn. As a result, they found that during the evaluation with the system installed there was an increase in driving within the speed limit, an increase in safe following distance, and less abrupt braking. However, once the device was removed, the drivers reverted to their previous bad habits. The study involved middle-aged drivers and only lasted 20 weeks, which may have not been sufficient time to change bad driving habits formed over years of driving.

A survey of ISA will find that there is little literature discussing the use of ISA in the United States. However, a review of ISA with application in reducing pedestrian fatalities was prepared by Texas A&M University (Jozwiak, 2000). This paper discusses current methods to reduce speeding in the United States, and the potential for ISA in the United States. There are generally four categories of speed reduction strategies in the U.S.: roadway design techniques (e.g. cul-de-sacs), roadway surface techniques (e.g. speed humps), traffic control techniques (e.g. speed signs), and enforcement techniques (e.g. law enforcement). The conclusion of this paper was that ISA could be used as a more effective method to reduce driver speed in pedestrian zones, thus reducing the number of pedestrian fatalities caused by speeding motorists. However, to date there has been no known evaluation or field study of ISA systems in the U.S.

2.1.2 Curve Speed Warning

One relevant research project involving a curve speed warning system was recently conducted by the University of Michigan Transportation Research Institute (UMTRI) along with some industry partners (UMTRI, 2003; Emery, L., Bezzina, LeBlanc, Sayer, Bogard, & Pomerleau, 2005). The project goal was to develop and evaluate a system that would prevent road departure crashes by warning the driver of impending road departure. The system included two functionalities: a lane departure warning subsystem and a Curve Speed Warning (CSW) subsystem. The CSW system utilized information from both the Global Positioning System (GPS) and an accurate digital map to determine a safe negotiating speed for upcoming curves. Information from onboard radar and a camera were also used to enhance the estimation of the vehicle's current position on the road. If the vehicle speed was exceeding the safe speed to negotiate the curve determined by the system, the driver was warned using visual, auditory, and/or haptic feedback signals.

A field test of the system was conducted using 11 test vehicles and 78 participants. Each participant drove the vehicle for four (4) weeks - one week as a baseline without the feedback turned on, and 3 weeks with the feedback turned on. In comparison to the baseline, the system also showed that with the warnings enabled, there was a 53% reduction in road departure or near-departure events. The preliminary results of this project also showed that there was an overall perceived effectiveness and acceptance by the participants. Most drivers felt the system made them more aware of their position on the road and of upcoming curves.

2.1.3 Weather-based Variable Speed Limit

There have been several documented cases of using weather data to dynamically determine a safe operating speed limit. A recent publication provides a state by state overview of DOT weather management safety practices (Goodwin, 2003). Although this report does not document any states that use weather information as part of an in-vehicle warning system, several states have developed roadside Dynamic Message Signs (DMS) and/or Variable Speed Limit (VSL) signs. In several of these states, a safe operating speed is determined using the respective state's Road Weather Information Service (RWIS), and roadside speed limits are reduced based on the severity of the weather data collected by the RWIS. The practice of determining an appropriate speed as part of a roadside VSL system is similar to what would be required to implement an in-vehicle VSL system. The only difference would be that in the in-vehicle system, an on-board computer is responsible for the data collection, processing, and speed notification as opposed to a fixed roadside display. The cases of VSL discussed in the Goodwin paper provide the methodology by which speed limits were reduced by the TDSS. Hence, this paper was used as a reference for developing the weather speed reduction algorithm for the TDSS.

2.1.4 Seatbelt Use

In a Transportation Research Board (TRB) report by the Committee for the Safety Belt Technology Study (2004), NHTSA conducted an evaluation of technologies to increase seatbelt use rates using in-depth interviews and focus groups involving several different age categories. The study was meant to evaluate the perceived effectiveness and acceptability of Ford and Saab's seatbelt reminder systems, and the use of Transmission and Entertainment interlocks. See the report titled: "*Buckle up: Technologies to increase seatbelt use*" for more details on the functionality of each system. The results of their evaluation showed that mean effectiveness and acceptability were lowest among males and the young (ages 17-25) category of drivers for all technologies except the entertainment interlock. Males and younger drivers rated the entertainment interlock higher than females and older drivers. All groups rated the reminder systems to have a higher acceptability than interlocks. However, all groups rated the interlocks to have a higher effectiveness than reminder systems. As a result of their evaluation the committee recommends that use of interlock technologies should be reserved for high risk groups such as teen drivers.

A separate TRB report, NCHRP report 500 (Volume 11), *A guide for increasing seatbelt use,* provides recommendations of what can be done from a non-technical standpoint (Lucke, Raub, Pfefer, et al., 2004). The report outlines a plan to increase seatbelt use by increasing public awareness of occupant restraint laws and increasing enforcement of those laws. This plan would be carried out through strategies such as public awareness campaign, education, and the enactment of local laws that enforce restraint use. These recommendations were taken into consideration during the initial development of the TDSS, and as a result, the use of TDSS could satisfy these recommendations. By incorporating the TDSS into local licensing laws, such as GDL programs, the TDSS could become both a tool for enforcement and improved driver education.

2.1.5 Alcohol Interlock

There has been no evaluation of alcohol ignition interlock systems and young drivers. Alcohol interlocks are generally reserved for use by persons with repeat Driving Under the Influence (DUI) offenses, who are generally in older age categories. Thus, evaluations of interlock programs have typically involved participants who have already been convicted of repeat offences. Results across these evaluations have shown similar results - interlocks are effective in preventing recidivism during the period of installation, but once the interlock is removed the recidivism rate appears to be similar to those who have not had the device installed (Beirness, 2001). One could speculate that repeat offenders may be predisposed to have a higher rate of recidivism than average drivers. However, one conclusion that is made with certainty from these evaluations is that interlocks are still an effective means to prevent drinking and driving when they are installed. There is some uncertainty about the long term effectiveness among older repeat offenders, but the long term effectiveness of these devices among young drivers has yet to be evaluated. An evaluation of their effectiveness in the circumstance where they are installed prior to offenses also has not been conducted, but would provided relevant information to this project.

2.1.6 ITS Technology and Teenagers

Aside from focus groups, there has been no other evaluation of ITS in-vehicle technology and teen drivers. Research on driver assistive technology to date has not focused on teenagers specifically. This is alarming given their high risk of crash and injury when behind the wheel. Although there have been a number of research evaluations of this technology among older drivers, the following summary discusses only one known example of past research that has focused on the use of in-vehicle technology specifically among young drivers, but again this research project only involved focus groups and not an actual field study.

In a 2003 study by an Australian group (Young, Regan, Mitsopoulus, & Haworth), a system was proposed with similar technology to the TDSS system. The study used focus groups held with 58 urban and rural young drivers between the ages of 17 and 25 to discuss the perceived acceptability and price they would pay for these and many other ITS devices. The technologies that were evaluated included ISA; forward collision warning; following distance warning; lane departure warning; fatigue warning; alcohol interlock and sniffer system; seatbelt interlock and reminder; and electronic licensing. As a result of the study, the proposed system would include ISA, the alcohol interlock system, and the seatbelt reminder system. The alcohol interlock and seatbelt reminder were chosen partially because these devices had the highest acceptability ratings. The results showed that the ISA system had a low acceptability, but the authors still believed the system to be an effective method to address speeding. These systems were also chosen because they could be produced in the short term at a price participants would be willing to pay. This study was the first phase of a larger evaluation of these technologies and young drivers. In proceeding phases, they intend to instrument vehicles with these technologies and conduct actual field evaluations. At the time of the writing of this document, the field evaluations have not been conducted and it is not known if this phase of the project has been funded.

2.2 Review of Existing Teen Driver Monitor Devices

Using technology to monitor driver behavior has been around for decades. Truck drivers and other fleet-type drivers have been monitored while behind the wheel. Products like the RS-3000 by Road Safety International have been used to record operating parameters of ambulance drivers. Road Safety International reports claims of improved driver behavior resulting from the use of such technology (Road Safety International, 2006). DriveCam, a company selling in-vehicles cameras for commercial vehicles, reports a 35-70 percent reduction in collisions among their customers (DriveCam, 2004). However, the need for new solutions to the teen driver problem has been realized by Road Safety International, DriveCam and several other companies, who have recently extended their technology for use by teenagers.

There are several teen devices currently on the market, which are fundamentally similar. Ultimately, these devices are monitoring systems. Most of the devices record driving parameters such as drive time, distance, maximum speed, throttle use, and location. A small number of systems include a feedback mode, with the thresholds (for speed and acceleration) being user defined. In such system, if a threshold is exceeded, an auditory signal alerts the driver and the instance is recorded for later review by a parent. A recent article in *Consumer Reports* (July 2006) describes the functionality of two systems intended for use by teenagers: the Road Safety system and the CarChip E/X. The report concludes that the Road Safety is the superior system because it provides instantaneous audio alarms to the driver based on excessive acceleration, braking, and hard cornering, which the CarChip does not. These devices range in cost from about \$200 to over \$1000, with the more advanced devices having on-board GPS to monitor and record the location of the driver.

In Appendix A, Figure A-1 compares several of these traffic safety devices according to their features and Table A-1 gives a descriptive summary of each device. By classifying them according to the methods of forcing, feedback, and reporting, we see from Appendix A, Figure A-1 that none of these devices offer a forcing function. A limited number of systems offer a feedback function, but most devices are primarily reporting-type systems. Refer to section 3.2 of this thesis for more information on what is meant by a forcing, feedback, or reporting function. Table A-1 of Appendix A also includes describes how each of these devices are integrated for use in the vehicle and the limitations of each device.

Since these devices only offer reporting and limited feedback features, they may be too passive, and do not utilize the full potential of their technology. For example, systems offering GPS-based position monitoring are only used to track the location of the teen driver; they do not correlate vehicle position to local speed limits or recommend speeds. In devices with speed feedback, the parent statically defines the speed threshold. This means the devices do not take into account varying speed limits and speed reductions necessary for safe vehicle operation in changing situations. Combined with digital maps, GPS has the ability to locate a vehicle's current position on the road to determine local speed limits, and identify upcoming curves to determine if the vehicle speed is appropriate for that road's local curvature.

In addition, no device requires seatbelt use or sobriety prior to vehicle operation. Two systems currently have a seatbelt recording or feedback option, but the systems do not prevent vehicle operation if the driver's seatbelt is disconnected. While there are alcohol ignition interlocks on the market, no teen technology device includes a feature to detect alcohol presence and prevent the operation of the vehicle if alcohol is detected. An alcohol ignition interlock feature would go beyond recording alcohol level; it would also ensure that the driver is sober before driving.

2.3 Other In-vehicle Technologies

The systems described in the preceding section have been marketed for use among teen drivers, if not developed specifically for use by teenagers. There are also a number of other products that have been developed for the purpose of recording or monitoring safe driving behavior. These products, which are described below, are not specifically marketed for use by teenagers, but they represent other technologies that are certainly relevant to this project because of they have some features that are similar to those included in the TDSS.

Progressive Auto Insurance (2004) is currently conducting a pilot study using a driver-monitoring device called TripSensor™ (patent #5,797,134). The device has been offered to 5000 drivers in Minnesota, and it tracks how much, when, and how fast they drive. Drivers with the device can receive up to a 25% discount through low-risk driving. A similar device is also being tested in a pilot study by Norwich Union (2004), the largest insurance company in the UK. The Pay As You Drive™ device is licensed under Progressive's patent application and tracks how much, when, and where a vehicle is driven.

A commercial speed alert product called the Otto Driving Companion is currently being sold in Canada by Persentech (Persentech Inc., 2005). The dashboard mounted device combines vehicle positioning and speed information from GPS with a digital road map containing sign locations in a few select metropolitan areas in Canada. Using a small integrated speaker, the device alerts the driver using voice commands if they are approaching a new speed limit, crosswalk, deer crossing, school zone, hazardous intersection, or red light camera. The device will also warn the driver is they are exceeding the road's posted speed limit. The product is marketed to all drivers as a safety device, but the product does incorporate conflicting messages. The device will also alert a driver if they are approaching a red light camera so they can avoid speeding tickets when they choose to exceed the speed limit.

Another speed alerting product called the Road Angel is currently being offered in the UK by Blackspot Interactive (Blackspot Interactive, Ltd, 2006). The Road Angel is an aftermarket dashboard mounted device that is built around GPS and a speed limit database in the UK. The system uses voice alerts and a visual display to notify the driver of advisory speed limits, road safety camera locations (speed cameras), accident blackspots (high accident zones), school zones, and congestions zones. The device uses a publicly available database of road camera locations, which is intentionally made public so that drivers know to reduce their speed in these safety zones.

A "black box" data retrieval system is available from Vetronix called the Crash Data Retrieval (CDR) System (Vetronix, 2004). The CDR is capable of extracting information saved in a vehicle's Event Data Recorder (EDR), which are available on several Ford and General Motors models, and a few select Isuzu vehicles. Only in the event of severe jolt, such as a crash, does the system record data. Information such as vehicle speed, engine speed, throttle position, brake status, seatbelt status, and acceleration rates can be captures up to five seconds prior to the impact. Information such as the brake status, seatbelt status, and acceleration rate would be useful to a TDSS if automobile manufactures made it available. As this device shows, this information can only be retrieved in the event of an accident, and only a five second window is captured. Since this information already exists within the vehicle's technology, the only limitation to using this data is its lack of accessibility. Therefore, manufacturers should improve the accessibility of this information so that driver safety technologies, like the TDSS can benefit from it.

A company called Altius Solutions, LLC has developed the MACBOX telematic event data recorder and vehicle Trip Data Calculator (TDC) for research and commercial purposes (Altius Solutions LLC., 2002). Both systems use Short Message Service (SMS) to send vehicle data over a wireless network and utilize GPS to record vehicle coordinates (not with respect to a digital map). The MACBOX contains on-board accelerometers, and will send a request for emergency response and details of the crash severity in the event of a crash. The MACBOX can also record seat-belt use, brake use, and other optional user specified parameters. The TDC device has similar functionality to the MACBOX, but does not have on-board accelerometers or crash notification. Instead, the TDC is more of a driver monitoring device capable of sending vehicle data (GPS coordinates, mileage, start/stop times, seatbelt use, brake use etc.) using SMS, and it also can be interfaced with vehicle's data bus. The reason this device has been included in this list is because it presents an example of a system that uses SMS text messaging to provide real-time information about the vehicle's status. SMS messaging, which is made available by most cellular providers, is a useful method to send small amounts of information over an existing wireless network.

Lastly, a product that aims to ensure drivers wear their seatbelt has been developed by a small company called D&D Innovations, Inc (Committee for the Safety Belt Technology Study, 2004). The Seatbelt Shifter Lock product has been developed to work on General Motors' vehicles. It prevents the shifter from being shifted out of park until the driver has fastened their seatbelt. The device has yet to be put on the market.

3. Methods of Behavioral Modification

3.1 Behavior Modification Functions

The TDSS made use of three behavior modification functions to addresses the risk behaviors associated with teen driver crashes. These functions are categorized as forcing, feedback, or reporting functions. Thus, the goal was to incorporate technologies that integrate these functions. These functions are intended to mitigate the critical risk behaviors, and thus result in a reduction in crash risk for teen drivers. A general description of each function is given in the following sections.

3.1.1 Forcing Functions

The first type of intervention function used by the TDSS is the forcing function. A forcing function is a type of technology that forces actions in a safe sequence prior to vehicle operation, or prohibits vehicle operation while an undesired behavior persists. The forcing function works by directly impacting behaviors, by affording safe behaviors and blocking unsafe behaviors. Indirectly, as the forced safe behavior is repeated, habitual compliance may be expected, and the resulting good habit should remain even after the forcing function is removed. Alternatively, the device can remain in place until the driver matures to a point in their life in which they recognize the importance of the safe behavior.

3.1.2 Feedback Functions

The next type of intervention function that is used by the TDSS is the feedback function. A feedback function can be a real-time auditory, haptic, or other sensory signal triggered during unsafe vehicle operation. This function primarily works by augmenting driver performance through feedback used as part of the learning process. This type of function provides the driver a behind the wheel education as to the limits of safe driving. A feedback-based system continually monitors the driver's behavior, providing notification whenever the driver has, or is about to, exceed such a safety limit.

Since some teenagers may not posses the skill or understanding to gauge the limits of safe driving, the feedback function provides contextual cues to help them learn to drive within safe vehicle operational parameters. For example, excessive speed or failure to reduce speed may trigger the system to warn the driver prior to entering a curve. This type of feedback is useful to the driver because the system identifies and notifies a teen driver of a dangerous situation before it occurs, or before it is too late to correct. If the driver does not comply with the warning, the warning continues, and/or becomes more severe, "hassling" the driver until the behavior is corrected. In this way, the system provides cues for the driver to learn safe operation in constantly changing situations. In many instances the driver can also use the feedback as a forewarning of danger, as in a possible curve situation where the driver may not have been prepared to otherwise negotiate the turn.

3.1.3 Reporting Functions

The last type of intervention function that is used by the TDSS is the reporting function. A reporting function captures and logs driver performance and situational information when the vehicle is being driven outside the parameters of safe driving for later review. Reporting functions give parents or other authorities in the social environment of the teen driver insight into how the teen is driving. This insight can enable these social agents to influence the learning experience of the teen driver. Notably, the use of the reporting function by parents and other authorities provides a tool that facilitates consequences for risky behaviors and rewards safe behaviors. This can motivate teen driver decision making toward safer driving by curbing risk taking tendencies associated with teen personality traits and by promoting more accurate risk assessments (by assigning immediate consequences to reported risky behavior). The (delayed) feedback process of reviewing these reports and assigning rewards for improvements can also facilitate the learning of safe driving habits.

Reporting can also occur in real-time. A real-time system has the ability to immediately notify the parent or authority when the teen is driving in an unsafe manner. Teens having prior knowledge of the reporting of their unsafe operation of the vehicle are aware of the possible consequences associated with their improper driving behavior, which may influence their decision to refrain from taking such risks.

4. Components/Modules

4.1 Background

The TDSS was built around the ideas, objectives, and constraints that were described in the previous sections of this document; and the technologies that were selected or developed as part of the TDSS were chosen by their ability to force behavior, provide driver feedback, and report driver behavior. Table 4-1 shows the technologies included in the TDSS and lists the functions that contribute to each feature. The TDSS was developed using components that were selected to specifically address the safety related factors among young and inexperienced drivers. Each component was integrated into a single unit that formed the TDSS. These technologies have potential for long-term reductions in crashes and crash related fatalities since teenagers have the ability to learn proper driving behavior early in their life. An appropriate goal for these technologies is to correct behavior while it occurs and before the behavior becomes habitual. Ideally, the teen will then carry forward the proper learned behavior into adulthood.

The components of the TDSS take advantage of past, existing, emerging, and new technologies. The TDSS borrows ideas from ISA, seatbelt and alcohol interlock systems, biometric fingerprint identification, SMS messaging, and current teen driver systems. However, the TDSS is the first time that all of these technologies have been combined to form a single support system that focuses specifically on teen safety issues. Despite the fact that some of these technologies may exist in some form, whether it be for commercial or research purposes, each component of the TDSS had to be developed for this specific application. For example, since ISA is an emerging technology, it only exists in limited forms used for research purposes, and there has not been an ISA system developed in the United States. An overview of ISA and the technologies that make up the TDSS are described in the following section. A summary of the technologies included in the TDSS is also given in Appendix B. The following section, 4.2, outlines the basic functionality of each component of the TDSS.

Table 4-1: Components of TDSS and their contributing functions

Component	**Contributing Function(s)**
Intelligent Speed Adaptation	Feedback & Reporting
Seatbelt Interlock	Forcing, Feedback, & Reporting
Alcohol Interlock	Forcing & Reporting
Data Reporting (Off-line & Real-time)	Reporting
Fingerprint Identification	Reporting
Driver Interface	Feedback

4.1.1 Intelligent Speed Adaptation

ISA is a behavioral modification technology that enforces the road's current speed limit. In simple terms, ISA can be described as a navigation system that adds speed limits to the digital map so that the vehicle 'knows' the maximum limit (Thomas, 2003). This technology is generally implemented through the use of GPS, digital maps, and a speed limit database. Additional features of ISA systems can include other types of speed warning, such as weather-based, or for curves. Local speed limits are determined based on the vehicle's location and then compared to the driver's current speed. Speed information can be conveyed to the driver in the form of auditory, visual, haptic interfaces. Or, a direct link to the vehicle's power train can prevent the vehicle from exceeding as speed limit depending on what category of system is used.

ISA systems are generally categorized into three warning types. The first warning type is an advisory system. Advisory systems provide an in-vehicle audio, visual, or haptic warning of unsafe speed. The second warning type is a mandatory system. Mandatory systems physically prevent the vehicle from exceeding a safe speed. The third warning type is a voluntary system. Voluntary systems are an advisory system with a mandatory feature that can be disabled.

There are also three types of notification levels for ISA systems. The first level is fixed notification. In a fixed notification system, warnings are based on posted speed limit only. The second level is variable notification. In a variable notification system, speed limits are additionally based on site specific recommendations such as curves, work zones, and school zones. The third level is dynamic notification. In dynamic systems, speed limits are also based on hazard potential such as weather and traffic conditions. Each additional level adds complexity to the system, and current technology and costs limits what type of system is used.

Although ISA is under extensive research overseas, it is still in its infancy. The primary limitation of implementing ISA is the lack of a suitable speed limit database. Road databases are currently available from several commercial vendors, and GPS technology can provide accurate position data, but there is also a need for accurate speed limit data to complete the system. The attention that ISA has received in Europe has raised the awareness of the need for a European speed limit database, but this awareness has yet to be realized in the United States.

4.1.2 Seatbelt Interlock

There are two varieties of seatbelt interlock: those which prevent the vehicle from starting via an ignition interlock, or those that prevent the vehicle from operating over a specific speed via a transmission interlock. There is also a different category of interlock called an entertainment interlock. This type of interlock does not prevent the vehicle from being started or driven, but instead prevents the entertainment features, such as the car radio, from being used until the seatbelt has been fastened. All vehicles currently manufactured contain much of the belt fastening sensing technology necessary to implement a seatbelt ignition interlock. More details on this and a description of how the interlock was implemented on the TDSS can be found in the following sections.

The idea of the seatbelt ignition interlock is several decades old. In 1973, NHTSA required all new passenger vehicles not having automatic restraint systems to come equipped with a seatbelt ignition interlock. The device required the driver to engage their seatbelt prior to starting the vehicle. However, resistance from the public ultimately led to an amendment of Federal Motor Vehicle Safety Standard (FMVSS) 208 passed by Congress in 1974, which restricted the universal deployment of seatbelt ignition interlocks.

Today's society has become much more accepting of seatbelts, as we continue to see an increase in seatbelt use over the years. In 2005, the nationally observed seatbelt use rates reached an all time high of 82% (Glassbrenner, 2005b), as compared to observations of around 10% when seatbelts were first required in passenger vehicles (NHTSA, 1997). Therefore, it may now be more socially acceptable to reintroduce this technology for high risk drivers such as teenagers.

Observational studies indicated that despite their low acceptance, interlocks were effective at increasing seatbelt use in the 1970's. Robertson (1974) showed that belt use was 59% in cars with interlocks as compared to 28% in car of prior model years. Therefore, it is reasonable to assume that interlocks would also be effective in increasing seatbelt use among today's drivers. Therefore, it is reasonable to assume that interlocks would also be effective in increasing seatbelt use among today's drivers.

The benefit of seatbelt use is well known. NHTSA (2004b) estimates seatbelts reduce the risk of fatality by as much as 45% for front seat occupants of passenger vehicles. However, despite their safety benefit, teen drivers continue to have the lowest belt usage rates compared to other age groups. Given the unreasonably low belt usage rates by teens, seatbelt ignition interlock technology must be considered as method to increase seatbelt use.

4.1.3 Alcohol Interlock

Alcohol ignition interlocks are a commercially available product available from a number of manufacturers (see Table 4-2). These devices are generally installed in the vehicles of repeat DUI offenders as a result of a court ordered punishment, but they may also be installed on a voluntary basis. There are currently over 70,000 devices in use in North American and forty-three states have legislation that allows interlocks to be installed in the vehicle of driver convicted of a DUI (Beirness & Simpson, 2003). In fact, current New Mexico law requires that *all* persons convicted of a DUI must obtain an interlock license, which would require them to have an approved interlock device installed in their vehicle.

The basic functionality of most systems is similar. Alcohol ignition interlock devices require the driver to complete and pass a breath alcohol test prior to vehicle operation. The driver's measured Breath Alcohol Concentration (BrAC), which corresponds to their BAC, must not exceed a pre-programmed threshold. If the device measures a (BrAC) above the threshold, the ignition is disabled, and the vehicle will not start.

Table 4-2: Alcohol ignition interlock manufacturers

Manufacturer	Website
1. Guardian Interlock	www.guardianinterlock.com
2. Autosense International	San Jose, CA (no web site)
3. Consumer Safety Technology, Inc.	www.intoxalock.com
4. Draeger Interlock, Inc.	www.ignitioninterlock.com
5. Lifesafer Interlock, Inc.	www.lifesafer.com
6. Smart Start, Inc.	www.smartstartinc.com
7. Alcohol Countermeasures Systems, Corp.	www.acs-corp.com
8. Alcohol Detection Systems	www.stopdwi.com
9. Monitech Inc.	www.monitechinc.com

4.1.4 Data Logger

Most drivers are currently unaware of a data logging system that is already installed in many vehicles. As discussed in section 2.3, many new automobiles from Ford and General Motors are equipped with an EDR, a device that is similar in function to the black box found in airplanes. Manufacturers initially installed the automobile black box to collect data for airbag research, but the technology has remained since it provides important data that protects manufacturers against product liability charges (NHTSA).

Access to some (throttle use, engine RPM, vehicle speed) of the same information the EDR records can be gained in real-time via the car's 2nd generation On-Board Diagnostics (OBD-II) port, which has been available on 1996 and later year vehicle models. The OBD-II port facilitates improved access to measures of vehicle performance. This information can be recorded and processed by an onboard computer to determine if the vehicle is being driven within the parameters of operational safety. If the driver exceeds the safety limits, this information can be recorded for later review by a parent or other authority.

Real-time notification is also possible through wireless communications such as automated cell phone text messaging. Parents would then be notified at the time the unsafe driving occurred, and would have the ability to take immediate corrective action. Since the teen drive would have prior knowledge of the reporting of their unsafe operation of the vehicle, they are also aware of the possible consequences associated with their improper driving behavior, which may influence their decision to refrain from taking such risks.

4.1.5 Biometric Fingerprint Identification

Current biometric fingerprint technology is a low cost method to identify an individual, and thus can be used in the vehicle to identify the driver and a supervising adult (such as a parent). Fingerprint sensing technology can be purchased for around $100. Fingerprint readers identify a person by identifying their unique pattern of minutiae. Minutiae include the ridges, ridge endings, and bifurcating ridges on a person's finger. The fingerprint reader processes the relative locations of the minutiae using a special mathematical algorithm and stores an encrypted template of the person's fingerprint. The template of an enrolled user is then matched to a fingerprint for identification. Since location of minutiae is unique for every person, fingerprint readers can easily distinguish between enrolled users.

4.1.5 Driver Interface

A driver interface is responsible for providing feedback information to the driver. Most drivers may already be familiar with feedback systems in their car. Perhaps every time a driver sits in the driver seat of a vehicle an auditory warning reminds the driver to buckle their seatbelt. Feedback systems have been proven to be effective in this case. For example, Ford Motor Company has developed the Seat-Belt Minder™ system - a more persistent buzzer lasting up to five minutes. Among drivers using the system, 46% have said their belt use increased, and 79% have said they want a reminder system in their next vehicle (Williams & Wells, 2003).

For a properly equipped vehicle, this same feedback function can be extended to other driving dynamics such as warnings for aggressive driving, driving too fast for conditions, and seatbelt nonuse. Using information, such as throttle use and engine RPM, or through onboard accelerometers, it is possible to calculate in real-time, a limit for safe acceleration that if exceeded would be associated with loss of traction and vehicle control. A variety of other feedback modalities (such as visual and haptic) can also be activated by this technology, warning the driver to modify their driving behavior to within the parameters of safe vehicle operation for current conditions. However, the purpose of this project was to examine the feasibility of integrating technologies for a proof of concept for a TDSS rather than to specify a specific form of interface.

4.2 Basic Functionality of TDSS Featured Components

There are two categories of components that were selected for the TDSS. The first category is the featured components. These are the components that were integrated into the final demonstration unit. For the case of the featured components, some of these technologies have been developed for research, and even consumer applications, but they are not at a stage of universal deployment, or they are not currently available for purchase, or they did not suit the specific requirements of the TDSS. Therefore, some of the components had to be specifically developed for this project. The second category of components is the optional component – the alcohol interlock. This technology was selected for investigation because of its potential for use in a TDSS. It was not integrated as part of the TDSS because these are already commercially available as an "off the shelf" product that could be purchased for use with the TDSS. Furthermore, it was not within the scope of this project to reinvent already existing technology like the alcohol interlock that was considered sufficiently capable of addressing their intended goal for safety.

4.2.1 Speed Limit Component

The speed limit component of the TDSS was based on the emerging ISA concept implemented in various forms in Europe. This component had to be specifically developed for this project. For the TDSS, an advisory warning with fixed notification was chosen, with features of the variable and dynamic systems also included. The feature of the variable system that was included is a curve notification subcomponent that alerts the driver of upcoming curves, and the advisory speed for the curve. The feature of the dynamic system that was included is a dynamic weather-based speed limit subcomponent. The details of the curve-speed and weather component are described in more detail in sections 4.2.2 and 4.2.3, respectively. The remaining paragraphs of this section provide an overview of the TDSS speed limit component. All components of the ISA system feature feedback and reporting functions. Feedback warnings in the form of audio messages were used to enforce safe travel speeds and are described in detail in section 4.4. In addition to the feedback, the system also used reporting features to record instances in which there was a lack of compliance. More details on the reporting features are given in section 4.1.6.

The speed limit component of the TDSS provides the driver with location based speed limit information and feedback when the driver exceeds the road's posted speed limit. This component is designed to make the driver conscious of their speed, and to condition the driver to drive at safe travel speeds. To do this, the system automatically notifies the driver of changes in the speed limit, and reminds the driver of the speed limit if they continue to speed. It will continue to warn the driver until their speed is reduced to within the legal limit. The system also notifies the driver of the speed limit when entering a new road so the driver can always be conscious of appropriate speeds.

The idea behind this ISA system seems trivial; to compare the vehicle speed to the speed limit and warn the driver when the vehicle speed is greater than the limit is a simple idea. However, the implementation of an ISA system is not a trivial task. To do this, the onboard computer requires information about the vehicle's location, speed, heading, direction, and the speed limit. This information comes from four primary sources of data: GPS, OBD-II, the digital map, and the speed limit database. To make sense of this data, software was developed so the onboard computer could process this data in real-time, and initiate a warning to the driver when necessary, send a real-time report when necessary, and save the information to an internal log when necessary.

As previously mentioned, a major limitation of deploying an ISA system is the availability of usable speed limit database. For demonstration purposes only, it is possible to manually collect speed limit sign locations for a few routes, and then only drive those routes. However, one task of this project was to determine what data already exists and if that data was in a usable format, which could be integrated into the system and provide speed limit coverage over a large geographic region. We found a usable speed limit database in Hennepin County. Other nearby counties and cities either did not have speed limit information readily available, or did not have it in a usable format. Therefore, based on this data availability, the TDSS was designed for demonstration in Hennepin County only. Much more detail on the speed limit database is given in the following chapters, but it is important to note that obtaining usable speed limit data is a major limitation to the widespread deployment of ISA, both locally and the rest of United States. To implement the other components (curve speed and weather) of the ISA system, data limitations were also realized, as is discussed in the following sections.

4.2.2 Curve Speed Component

The curve speed component of the TDSS was a subcomponent of the speed limit component and is categorized as variable notification feature of ISA. The basic functionality of the curve speed component is to warn the driver of upcoming curve(s) with sufficient time to react, and notify the driver if the vehicle speed is too great to negotiate the upcoming curve. In this way, the TDSS system not only provides static (speed limit) speed information to the driver, but also contextual based speed information based on road geometry. The curve speed component also demonstrates another potential application of available speed data.

The curve speed component functions in a similar way to the speed limit component. The system collects information from the GPS, OBD-II, the digital map, and a database of advisory curve speeds. Software was developed so the onboard computer could process this data in real-time, initiate a warning to the driver when necessary, and save the information to an internal log when necessary. When the vehicle approaches a curve in the database, for which an advisory speed exists, the TDSS system notifies the driver prior to entering the curve of the direction of the curve (left or right) and the advisory curve speed. The system notifies the driver of the upcoming curve with sufficient time to slow down, and will warn the driver if the vehicle's speed is not appropriate for the curve. If the driver continues at a speed higher than the advisory curve speed, the system will continue to notify the driver, and will remind the driver of the advisory curve speed until the vehicle has passed the curve. Not only does this condition the driver to drive within safe limits, but it is also useful in situations were the driver may be unfamiliar with the road geometry, and could potentially alert an inattentive driver of a necessary maneuver before it is too late.

Since advisory curve speed data availability was also an issue, the curve-speed component could only be developed for demonstration on county roads in Hennepin County. The data came from curve survey sheets recorded by Hennepin County traffic engineers. It should be noted that this data only pertains to county roads in Hennepin County, but does not include county roads within the city limits since local and state traffic engineers have jurisdiction over these roads.

4.2.3 Weather Component

The weather component of the TDSS was also a subcomponent of the speed limit component and is categorized as dynamic notification feature of ISA. The purpose of this component was to collect current weather information and provide the driver with a safe speed based on the prevailing conditions. Since beginning drivers may be unfamiliar with driving in adverse weather conditions, this system provides the driver with a metric by which safe speeds could be learned.

Weather data is collected from Minnesota's RWIS. RWIS is a weather information service developed by Surface Systems, Inc (SSI) (www.ssiweather.com) and has been implemented around the country for the purpose of monitoring road and weather conditions. Currently 46 states use an RWIS provided by SSI, including Minnesota. The system consists of a suite of sensors that collect real-time weather and pavement data. The pavement sensors measure temperature, freeze point, moisture, form of moisture (snow/ice), and amount of deicing chemical present. Atmospheric sensors are placed adjacent to the pavement and measure air temperature, relative humidity, wind speed and direction, precipitation type, intensity and rate, and visibility. The data from each sensor site is connected to a remote processing unit, which collects and transmits the data to a central server where transportation agencies can access the data.

The Minnesota RWIS network is maintained by the Minnesota Department of Transportation's (Mn/DOT's) Office of Maintenance. There are sensor site locations throughout the state of Minnesota, 8 of which are located in the metro region. Figure 4-1 below shows a map of RWIS sensor site locations in the Minnesota metro region. RWIS site locations are designated by the triangle icons. As can be seen in Figure 4-1, there are only two sensors located in Hennepin County. Tables C-1, C-2, and C-3 of Appendix C list the type of data can be collected at each specific site. Table C-4 of Appendix C shows the identification number and location of each site in the metro region.

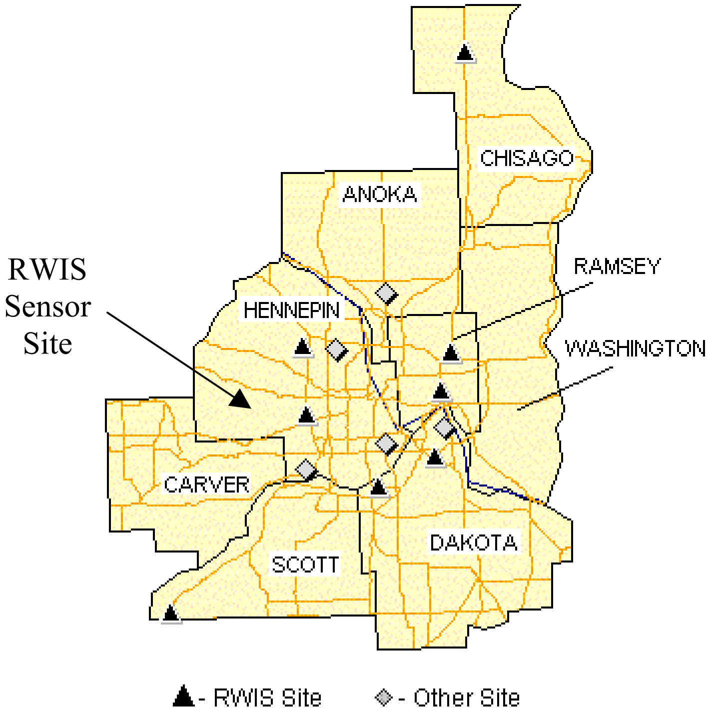

Figure 4-1: Map of Minnesota metro RWIS sensor site locations

In the demonstration TDSS, the system uses a General Packet Radio Service (GPRS) cellular modem to download current weather conditions from RWIS once every ten minutes (RWIS data is collected and updated every ten minutes on the RWIS server). Once the data is downloaded, the TDSS determines the closest site to vehicle's position, and the data from the closest site is used as the basis for determining an appropriate speed limit. If the weather is clear, there is no reduction in speed limit, but if the TDSS detects adverse weather conditions, the driver is notified of prevailing adverse conditions, and the speed limit is adjusted based on the severity of the condition.

A software algorithm was developed to process the RWIS data, and determine if a speed reduction is required, and if so, by how much. The algorithm was based on the published practices by several DOTs that use RWIS data in variable speed reduction and warning systems (Goodwin, 2003). More information on the software algorithm and the DOT practices upon which the algorithm is based can be found in section 7.6.

4.2.4 Seatbelt Component

The seatbelt component is an important feature of the TDSS because this component is responsible for developing a habit of wearing the seatbelt by the driver. This is accomplished by the means of a forcing, feedback, *and* reporting function for seatbelt use. The forcing function developed for demonstration is a basic seatbelt interlock. The interlock prevents the vehicle from being started until the seatbelt is engaged. Therefore, the driver must fasten the seatbelt prior to starting the vehicle. The system also continuously monitors the status of the driver seatbelt switch once the vehicle has been started. If the driver disengages their seatbelt while the vehicle is in motion, the TDSS alerts the driver to fasten their seatbelt. If the seatbelt warning is ignored past a specified time threshold, a real-time report is sent to the parent. Each time the driver disengages their seatbelt while driving, the TDSS also makes a record of the instance within the system's internal log. The system will continue to warn the driver of the seatbelt violation until the seatbelt has been engaged or the driver comes to stop. The system will not warn the driver if their seatbelt is disengaged while stopped with the vehicle running since there may be situations where the driver may need to exit the vehicle temporarily, and this was not considered to be a safety issue.

4.2.5 Driver Identification Component

The driver identification component serves several purposes, and could additionally enable the inclusion of many other potential features of the TDSS. The driver identification component makes use of a biometric fingerprint reader to enroll, capture, and identify the driver and parent/supervisor's fingerprint. Therefore, it is a part of the reporting features of the TDSS. Prior to driving, the driver and parent/supervisor's fingerprint are enrolled along with their name and age. This information is saved to the systems memory so that the TDSS can capture the identity and age of those enrolled users upon startup.

The driver identification component was included to demonstrate that the system could give parents the option of disabling the system. Since the driver is required to enroll their fingerprint upon startup, if the driver is identified as a supervisor, the system will be disabled and will not record any information. This feature provides the means for the parent to opt out of the system and maintain their privacy if desired. If the driver fingerprint is not recognized as a supervisor, the system remains fully functional and will prompt the supervisor to enroll their fingerprint.

The driver identification component also enables the enforcement of current GDL restrictions, and could be used to enforce future GDL recommendations. Table 4-3 gives a breakdown of current GDL restriction and the number of states with each restriction. (Note that the number of states listed does not necessarily mean that each of these states meets the IIHS recommendation. It only means that the state has some type of restriction in place.) There are currently two restrictions that are enforceable by the TDSS: the minimum number of hours of supervised driving in the learner stage, and the nighttime unsupervised driving restriction.

Since the TDSS records the presence the driver and supervisor, the number of supervised training hours can easily be monitored by the system. Under current GDL programs, there is no strict enforcement of this provision. Although driving with a supervised driver for a minimum number of hours is a requirement to pass from the learner to the intermediate stage, enforcement of this provision is strictly up to the parents. For example, in Minnesota, a driver in the learner stage is required to complete 30 hours of supervised driving, 10 of which must be at night. The parents confirm the completion of these training hours by signing a release allowing the driver to pass to the intermediate stage. The TDSS simplifies the task of keeping track of this information and ensures that the driver and parent have completed a sufficient number of training hours. Using the TDSS, this information could also be made available to the Department of Public Safety (DPS), so that DPS can verify the minimum number of hours has been satisfied.

Since the TDSS can record the presence of a supervised driver, the system is also capable of enforcing GDL restriction on unsupervised nighttime driving. By checking the driver's age and the current time, the system could require the presence of a supervised licensed adult if the driver is still in the intermediate stage and attempting to drive past the hours of the nighttime restriction. The type of enforcement could be configurable, but could include parental notification in this instance.

Table 4-3: Summary of current GDL restrictions in the United States
as of 3/06 (IIHS 2006)

Stage	Restriction	States (+ D.C.)	IIHS Recommended
Learner Stage	Minimum learner permit age	51	16
	Mandatory holding period	49	6 months
	Minimum hours of supervised driving	40	30 - 50
	Cell phone use	10	
Intermediate Stage	Minimum intermediate license age	46	16 years 6 months
	Nighttime unsupervised driving	45	9/10pm-5am
	Number/Age of passengers	35	1 teenager
	Cell phone use	8	

In addition to enforcing current GDL restrictions, the TDSS is also capable of enforcing GDL recommendations that could potentially become part of GDL if future programs meet the standards set by IIHS. Perhaps future iterations of the TDSS could become more sophisticated and be designed specifically for use with GDL programs. One such restriction the TDSS is capable of enforcing is a seatbelt requirement since the TDSS includes a component to monitor and record seatbelt use. If this were the case, the TDSS could include components that not only recognize the driver and supervisor, but all passengers to enforce the passenger restriction. Additionally, the system could include a component to block cell phone use while the vehicle is being operated.

4.1.6 Reporting Component

The vehicle data logger is responsible for processing and capturing information that can be used to facilitate the reporting features of a TDSS. There are two methods of reporting that can be used by a TDSS: real-time and off-line reporting. Real-time notification is possible through wireless communications such as automated cell phone dialing. Parents would then be notified at the time the unsafe driving occurred, and would have the ability to take immediate "corrective" action. A data recording system, built around an onboard computer, could capture information about the driver speed, seatbelt use, and alcohol presence for later review. It also allows capturing of other vehicle information and allows certain provisions of GDL systems to be enforced.

There are two methods of reporting used by the TDSS: real-time and offline reporting. The real-time reporting system makes use of the GPRS modem that is also used to download weather information from RWIS. The modem is capable of sending reports to a specified cellular phone number or to a specified e-mail address using SMS. The system can be configured based on the user specification as to when an appropriate instance to send a message has occurred, and what type of message they prefer, text message or e-mail.

For the demonstration set-up, messages are sent only when an infraction has been ignored past a specified time interval, or if the driver has exceeded a maximum speed threshold. The first instance that would cause a real-time message to be sent is when the driver has exceeded the speed limit past a specified time interval. This happens after the driver has been sufficiently warned to reduce speed, but continues to drive above the posted speed limit. The next instance that would cause a message to be sent is if the driver has driven with their seatbelt unfastened past a given time interval. The final instance that would cause a message to be sent is if the driver is speeding past a certain maximum defined speed, or if the driver has exceeded the speed limit by a maximum differential. Each report that is sent contains information that specifies the reason for the report, details of the report, and the driver's current location. Example reports that were received by cell phone are shown in pictures in Figure 4-2.

Message from:
6128193223
Excessive Speed:
79 in a 55, Road:
I-35W
03/08 4:02P

Message from:
6128193223
Not Wearing
Seatbelt past:
40 sec, Road:
Shoreline Dr

Figure 4-2: Example text message reports as viewed on a cell phone

In addition to the real time reporting system, the TDSS captures all instances within an internal performance log, which can be viewed later offline. The driver performance log records the same information that is sent in the real-time message plus additional information that provides much more detail. The log is organized in a format that is easy to understand by the user. An example log is shown in Appendix C, Table C-1. At the beginning of the log, the system writes the date and time, along with the names of the driver and supervisor that are present. Following this information, the log lists each infraction that has occurred starting with the time, and then lists the type of infraction, details of the infraction, and where the infraction occurred. The mile point location is also recorded so that the location of each infraction can be displayed on a street map, as shown in Appendix C, Figure C-1.

4.3 Optional Component

4.3.1 Alcohol Component

There are a number of reasons that the alcohol component is, for the time being, an optional component of the TDSS. Since commercially available alcohol ignition interlocks have most of the features that would be necessary for use with the TDSS, it was determined that this feature could be demonstrated as an “off-the-shelf” option. Many of the commercial devices allow programming of the BrAC threshold, which is necessary for the case teenagers since the device would need to be set at zero percent BrAC (zero tolerance) threshold. In addition to the forcing function that prevents the vehicle from starting, the devices also have the ability to capture event data, which records the driver’s BrAC each time the vehicle is started or attempted to be started. The commercial devices also contain some sophisticated features that prevent the user from defeating the system and to prevent false positives. More information about these devices can be found on their respective websites given in Table 4-2.

The other reasons this feature was reserved for use as an option and not a featured component were due to cost and convenience. Since alcohol ignition interlocks are generally installed on a non-voluntary basis, most manufacturers and distributors only offer the use of the interlocks as part of a lease program. This option is relatively expensive when considering the original constraint of keeping overall cost to a minimum. The lease programs generally cost around $60 per month ($500 annually), plus requires professional installation at an authorized service center. Since lease programs are intended for non-voluntary users, they require the user to visit the authorized service center frequently for data download and recalibration. Currently, no service centers are located in Minnesota. Therefore, leasing the device could potentially be a major inconvenience, which could deter a user from voluntarily installing this feature. Two manufacturers (Alcohol Countermeasures Systems and Alcohol Detection Systems) offer the option to purchase the device at a cost of approximately $800 for use on a voluntary basis. These devices must also be recalibrated every couple of months, but instead of visiting a service center, the device can be sent back to the manufacturer for recalibration at the user’s convenience. Purchasing the device currently would be the best option, and may save cost in the long run, but the initial price may still be too high.

For these reasons, the alcohol ignition interlock is being considered as an optional component, and it was not installed on the TDSS demonstration unit. A likely scenario is that the alcohol interlock component would be reserved for teen drivers with preexisting alcohol-related convictions. Evaluations of interlock programs have shown them to be effective in preventing recidivism during the period of installation (Beirness, 2001).

4.4 Driver Interface

In order to relay information to the driver in this proof of concept demonstration, a simple audio interface was developed. The purpose of the audio interface was to provide the driver with contextual based information about their current driving behavior, the current driving environment, and/or general system information. To convey a sufficient amount of information to the driver, speech based audio commands and notifications were used. It should be noted that the content of the message set for the speech interface was not optimized for this study. Rather, a basic message set was used only to demonstrate the feasibility of using speech as an interface method for this proof of concept demonstration. Future human factors research is needed to design an optimal interface both for the driver and the parent.

The speech commands were in the form of prerecorded computer voice generated WAV (16 KHz, 16-bit, mono) files. The files were downloaded from a research and evaluation website (http://public.research.att.com/~ttsweb/tts/demo.php#top) for AT&T's Natural Voices text-to-speech software. The software converts user entered text into audible speech, with options for choosing among several different languages and voices. A summary of the voice commands used for the TDSS and the situations in which the commands are triggered are summarized below. The following section is also useful in understanding the basic functionality of the system and how it operates.

Upon startup, the system will prompt the driver to enroll their fingerprint for identification using voice-prompt VPSI1 (See Table 4-4 for a description of voice-prompt acronyms). If the driver's fingerprint is successfully enrolled, the system notifies the driver using message VPSI3. If the fingerprint was not successfully enrolled, the system notifies the driver using message VPSI4, and then prompts the driver to make a second attempt using message VPSI2.

VPSI1	*"Please enter driver fingerprint in the next ten seconds"*
VPSI2	*"Please re-enter driver fingerprint in the next ten seconds"*
VPSI3	*"Fingerprint identification successful"*
VPSI4	*"Fingerprint identification failed"*

Once the driver fingerprint is successfully enrolled, the system checks the age of the driver. If the driver age is below the GDL predefined age that requires logging training hours with a supervised licensed adult (21 and over), the system asks for the supervisor to enroll their fingerprint using message VPSI5. If the fingerprint is successfully enrolled, the TDSS notifies the driver using message VPSI3. If the enrollment was not successfully entered, message VPSI4 is given followed by message VPSI6 to prompt the supervisor for a second attempt.

VPSI5	*"Please enter supervisor fingerprint in the next ten seconds"*
VPSI6	*"Please re-enter supervisor fingerprint in the next ten seconds"*

The first fingerprint enrolled is always the driver's. If the driver's fingerprint is recognized as a supervisor, and the age is 21 years or over, the system will be disabled and will not record driver data. In this case, the user is notified that the system has been disabled using message VPSI7.

VPSI7	*"TDSS is now disabled"*

Once the fingerprint enrollment procedure is completed, the TDSS will notify the driver that they may now begin driving using message VPSI8.

VPSI8	*"You may now start driving"*

If the system has not been disabled, the system continuously monitors both the driving environment and the driver's behavior. Feedback messages are triggered when there is either a change in the environment, or the driving behavior needs to be corrected. The messages provide detailed information to the driver, which gives the driver a clue as to why the message has been given and/or what type of corrective action needs to be taken.

For the case of driving above the speed limit, the TDSS provides the driver with a warning that indicates they are in violation of the posted speed limit using message VPBW1. If the vehicle speed remains above the speed limit, this warning message is given repetitiously every 5 seconds. If the vehicle speed is not reduced to within the speed limit after a specified amount of time, the system reminds the driver of the current posted speed limit using message VPDE1.

VPBW1	*"Exceeding speed limit"*
VPBW2	*"If speed violation continues, text message will be sent"*

Message VPDE1 is also used to notify the driver of the road's current speed limit if the vehicle enters a new road in the database. If the speed limit on the current road has changed, but the vehicle remains on the same road, message VPDE2 is used.

VPDE1	*"Speed limit: XX miles per hour"*
VPDE2	*"Speed limit changed to XX miles per hour"*

In addition to notifications based on excessive speed, notifications are also triggered if the TDSS detects excessive acceleration. Message VPBW3 is used in the situation of excessive acceleration to provide the driver with a metric for safe acceleration. This message is generally triggered at low speeds when high throttle use and high engine RPM are detected.

VPBW3	*"Excessive acceleration"*

Another type of speed notification is given when the vehicle is approaching a curve in the curve-speed database. In this situation the driver is notified of the curve's direction, and the advisory speed associated with the curve using message VPDE3. If the TDSS determines that the vehicle speed is too great prior to entering the curve, or if the vehicle speed is exceeding the advisory speed through the curve, message VPBW3 is used. If the vehicle speed continues to be higher than the advisory curve speed, the system will continue to notify the driver using message

VPBW3 and will also remind the driver of the advisory curve speed using message VPDE4 until the vehicle has passed the curve.

VPDE3	*"<Left/Right> curve, XX miles per hour"*
VPBW3	*"Exceeding curve speed"*
VPDE4	*"Curve speed, XX miles per hour"*

The TDSS also notifies the driver if adverse weather conditions have been detected. Since the system updates weather data every ten minutes, the weather notification only occurs after the time of the update. If no adverse weather conditions are detected, there will be no message. If adverse weather conditions are detected, message VPDE5 notifies the driver to listen for additional weather information. Following this, there is a message to detail the type of adverse weather condition (VPDE6, VPDE7, VPDE8, VPDE9, or VPDE10), and message VPSI9 is used if a speed reduction has gone into effect. If the severity of the weather condition is low enough, message VPSI9 is not given, and the system does not reduce the speed. If the weather is severe, and a speed reduction goes into effect, then message VPDE1 is used to notify the driver of the reduced speed limit. When weather based speed reduction is in effect, and the vehicle speed exceeds the safe limit set by the TDSS, message VPBW4 is used to notify the driver that the current speed may be unsafe.

VPDE5	*"Weather update"*
VPDE6	*"Roads may be slippery"*
VPDE7	*"Roads may be icy"*
VPDE8	*"Low visibility"*
VPDE9	*"High wind potential"*
VPDE10	*"Caution, wind advisory"*
VPSI9	*"Speed reduction in effect"*
VPBW4	*"Too fast for weather conditions"*

The driver is also notified if their seatbelt is not fastened. If the vehicle is in motion, and the system detects that the driver side seatbelt is disengaged, message VPBW5 is used. This message continues every five seconds until the seatbelt has been fastened, or until the vehicle comes to a stop. If the vehicle remains in motion, and the seatbelt is not engaged past a specified time period, message VPBW6 is used to warn the driver that a text message will be sent if the seatbelt is not fastened.

VPBW5	*"Fasten your seatbelt"*
VPBW6	*"If seatbelt violation continues, text message will be sent"*

Text messages are sent in the event that either the seatbelt is not engaged past a specified time period, or the vehicle speed remains above the speed limit for a specified time period. In both instances the driver is first notified (using message VPBW2 or VPBW6) that a text message will be sent if the violation continues. Once the warning has been initiated, the driver will have a randomly determined time period from 0 to 30 seconds to comply. If the driver fails to comply within the random time period, the driver will be notified that a text message has been sent using message VPSI10.

VPSI10	*"Text message has been sent"*

These messages represent the current state of operation of the demonstration TDSS unit. The TDSS can, of course, be reconfigured to play additional messages in other situations. However, the messages used in current version of the TDSS where chosen based on the feedback of several observers, and are intended for the purpose of demonstration only. To understand what types of messages and/or feedback modalities would be most effective, human factors testing should take place. Since human factors testing was not within the scope of this project, the auditory feedback system that was developed represents an example of how the system could operate, and is also used to convey the functionality of the system to the casual observer.

Table 4-4: Voice-prompt acronyms

Acronym	**Details**
VCSI#	**V**oice **P**rompt, **S**ystem **I**nformation, reference **#**
VCBW#	**V**oice **P**rompt, **B**ehavior **W**arning, reference **#**
VCDE#	**V**oice **P**rompt, **D**riving **E**nvironment, reference **#**

5. Equipment and Sensors

5.1 System Overview

The TDSS consists of an onboard computer and a number of external sensors and equipment that connect to the computer. All the equipment and sensors shown in Figure 5-1 make up the complete system. At the core of the TDSS is the in-vehicle computer built around a PC-104 platform, which serves as a hub for all the external devices. The peripheral devices that connect to the computer include a GPS receiver, cellular modem, fingerprint sensor, OBD-II adapter, seatbelt switch connection, and an audio adaptor. More details about each of these devices are described in the proceeding sections.

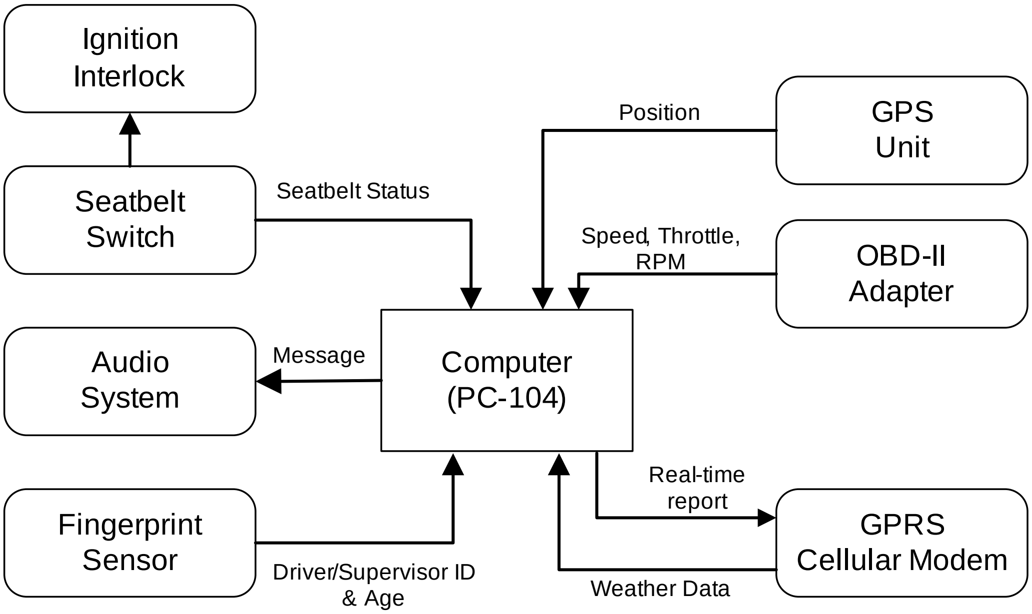

Figure 5-1: TDSS system diagram showing the computer and external devices

5.1.1 On-board Computer

The computer is responsible for collecting external information about the vehicle's current driving state, processing the information to determine if the vehicle is being driving within the limits of safety, and communicating (input/output) with external devices to trigger feedback responses to the driver. The computer uses the QNX (version 6.2.1) Neutrino real-time operating system and all software was developed in the C programming language. See Appendix E for the computer's technical specifications. Chapter 7 provides a more detailed explanation of the system's software.

For the purpose of connecting with the external devices, the computer has a number of ports for the input/output of data. The GPS receiver, cellular modem, OBD-II adapter, and fingerprint sensor all connect to a separate serial port on the computer. Through the serial ports, the computer can communicate with each device, and/or collect data and make data requests when necessary. The seatbelt switch is connected to an analog input port on the computer. Through this analog input port, the computer is able to determine the status (buckled/unbuckled) of the seatbelt based on a voltage reading. A stereo jack provides an audio output port to connect with the vehicle's audio system for the purpose of playing voice feedback messages using the car stereo speakers. For the purposes of testing, the computer also has an Ethernet port (not shown in Figure 5-1) for connecting a laptop to remotely upload software and download data.

5.1.2 Global Positioning System Receiver

The GPS receiver is responsible for providing position (latitude/longitude) updates to the system. For this project, a Garmin GPS18 (see Figure 5-2) device was used, which has a sampling rate of 1 Hz. This sampling rate is sufficient to maintain adequate response time between data samples and state computation to determine if driver feedback is necessary. The device uses correction signals from the Wide Area Augmentation System (WAAS) to improve accuracy, providing a specified position accuracy of less than 3 meters (95% typical) and a speed accuracy of 0.1 knots (95% typical). The GPS receiver connects to the TDSS computer via one of the computer's serial ports. Data is provided in the standard NMEA 0183 format, and the TDSS software collected necessary information from the GPGGA sentence.

Figure 5-2:
GPS receiver
(Garmin GPS18)

This Garmin GPS 18 was selected for a number of reasons. This device is designed specifically for OEM applications where size, cost, and performance are all considerations. The receiver is relatively low cost at approximately $90, which is significantly cheaper than expensive Differential GPS (DGPS) receivers that can cost on the order of thousands of dollars. The accuracy of a DGPS receiver was not determined to be necessary for the application of this project. DPGS can provide centimeter level accuracy, which is important for applications where high precision is required, such as lane departure warning systems. However, the primary purpose of the GPS receiver for this project was to provide sufficient accuracy that road positioning could be determined. The 3 meter accuracy of the Garmin GPS18 was more than enough, especially considering the digital map accuracy is published at approximately 40 meters. The other feature that makes this device attractive is the packaging. The device is completely self-contained in a single waterproof puck-style casing as shown in Figure 5-2. The device also has a strong magnetic base which allows it to be mounted virtually anywhere to the exterior of the vehicle.

5.1.3 OBD-II Interface Adaptor

The vehicle's on-board diagnostic port was used to collect vehicle performance information. Starting in 1996, OBD-II standard was required for all vehicles sold in the United States, making it universally available on 1996 and later vehicle models. This diagnostic port is conveniently located underneath the dashboard of the vehicle within the cab. Figure 5-3 shows the location of the diagnostic port, officially known as the vehicle's Data Link Connector (DLC), which is physically defined by the Society of Automotive Engineer (SAE) J1962 standard. This location under the dash on the Infinity M45 test vehicle is similar to most vehicles. The OBD-II port, as the DLC is generically referred to, facilitates access to diagnostic measures of vehicle performance provided by the vehicle's OEM diagnostic sensors. From the OBD-II port, the TDSS collects data measures of vehicle speed, engine RPM, and absolute throttle position. This data is collected by the onboard computer and processed by the TDSS software to determine if the vehicle is being driven within the parameters of operational safety.

Figure 5-3: OBD-II connector location
(Infinity M45 test vehicle shown)

The current hardware communication protocols for OBD-II are defined by Society of Automotive Engineers standards (SAE, 2003). Under the SAE J1850 OBD-II specifications, there are five electrical interface protocols in use: J1850 VPW, J1850 PWM, ISO9141-2, ISO14230 (KWP2000), and ISO15765-4 (Controller Area Network [CAN]). All vehicles sold in the United States are required to comply with one of these protocols. As a general rule, the J1850 VPW protocol is used by Ford, the J1850 PWM protocol is used by General Motors, and the ISO9141-2 protocol is used by Chrysler and import manufacturers. These three protocols (J1850 VPW, J1850 PWM, ISO9141-2) cover most the 1996 and later vehicles, but some also use the PWP2000 and CAN protocols. As a result of these standards defined by SAE, third party developers can now gain access to the diagnostic data made available through the OBD-II port.

The SAE J1850 OBD-II specification includes specific automotive electrical interface standards that are not compatible with industrial or commercial PC standards. Therefore an adapter must be used to convert the data to the RS-232 standard that is compatible with the TDSS computer. For this purpose, the AutoTap® OBD-II interface manufactured by B&B Electronics was used to translate RS-232 data to and from the onboard computer to the OBD-II equipped vehicle. Using the OBD-II adapter shown in Figure 5-4, the TDSS is able to collect measures of vehicle speed, engine RPM, and absolute throttle position using the data protocol defined by the SAE J1979 standard. This data is collected through the serial port of the onboard computer so that it can be processed by the TDSS software.

Figure 5-4: OBD-II interface adapter (AutoTap Pro model shown)

The current OBD-II standards are not without their limitations. The electrical hardware interfaces (other than CAN) only support a minimal data collection rate. Table 5-1 below shows the maximum bit rates supported by each interface protocol. The TDSS demonstration vehicle (2003 Infinity M45) used the ISO9141-2 standard, and data was collected at 2Hz without any trouble. Since the TDSS was designed around a processing rate of 1Hz, this data rate was sufficient. Although the current OBD-II hardware was sufficient for the purposes of this project, this may prove to a limitation in applications that require more precise timing or faster sampling rates when more data is transferred. Another limitation of the current OBD-II specification is that the SAE J1979 data standard only requires manufacturers to make the generic set of parameters available, so data access is universal to only these parameters. That means availability to the enhanced parameters – parameters not in the generic list – varies between manufacturers, and is not guaranteed that these parameters will be included. Since vehicle speed, throttle use, and engine RPM are included in the list of generic parameters, these parameters can be collected from any OBD-II compliant vehicle. However, it may be beneficial to collect other parameters from the vehicle.

Table 5-1: OBD-II standards and data bit rates

Electrical Standard	Data Rate
J1850 VPW	10.4 kbps
J1850 PWM	41.6 kbps
ISO9141-2	10.4 kbps
ISO14230-4 (KWP2000)	10.4 kbps
CAN	1.0 Mbps

Access to other vehicle sensor data such as seatbelt status can be collected by the manufacturer's own diagnostic tools, but it is not universally accessible by third party developers. Therefore, the TDSS is unable to collect this information through the OBD-II port. Access to the seatbelt switch status from the OBD-II port would eliminate the need to tap in to the seatbelt wiring directly, and would also eliminate the need for the analog/digital hardware in the TDSS computer. However, manufacturers have defined their own proprietary protocols and electrical interfaces for collecting this information, and they do not make it available to the public. Access to this and other possible information, such as the vehicle's onboard accelerometers (which are used in airbag sensing systems), would allow additional and perhaps even better performance evaluations than what can be measured only using speed, RPM, and throttle use.

Some of these limitations will be addressed by the CAN protocol, which will be required in all vehicles manufactured, starting in 2008. Some vehicles have been manufactured with the CAN protocol starting in 2003 (CAN was not allowed before this year) in preparation for the requirement. However, most vehicles still use one of the other protocols defined under the current OBD-II specifications. Therefore, future iterations of the TDSS will need to include hardware to support both the legacy protocols and CAN if the system is to be considered universal. Manufacturers of these adapters have prepared for the changeover and are producing adapters that support CAN. The major improvement of the CAN protocol over current protocols is the data acquisition rate. The CAN bus is capable of data rates of 1 Megabit per second. The fastest transfer rate under the current protocol is the J1850 PWM at 41.6 kilobits per second.

Access to a larger amount of information may also be possible under the CAN protocol. The CAN protocol achieves a faster data transmission rate because it allows direct access to the physical location in the Engine Control Unit (ECU) where the data is located. The other protocols include an additional layer that requires data to be collected through functional messages that communicate with the ECU's diagnostic network. That means that a request for data must first be sent to the network before a digital data response is given. These functional messages only allow communication with the legislated parameters that are included in the OBD-II requirements. Under the CAN protocol, if the physical location of the data is known, then virtually any sensor data that is processed by the ECU can be collected through the OBD-II port, and at a much higher acquisition rate.

5.1.4 Seatbelt Interlock and Monitor

The seatbelt interlock and monitor was designed and installed such that if the seatbelt is not engaged prior to starting the vehicle, the vehicle will not start. The vehicle will only start if the seatbelt is engaged. Consistent with current OEM operations, the vehicle will not "turn-off" if the seatbelt is disengaged while the vehicle is running. However, if the seatbelt is disengaged while the vehicle is turned on, a signal is supplied to the TDSS computer where it is processed by the software to initiating a warning to notify the driver their seatbelt should be engaged.

To understand the implementation of the interlock, some background on how the seatbelt switch operates is necessary. As a result of the seatbelt buzzer requirement mandated by NHTSA, all vehicles have wiring that runs to the driver side seatbelt. This wiring terminates at the vehicle's ECU, which is responsible for triggering the seatbelt reminder buzzer if the seatbelt is disconnected during start-up. If the seatbelt is engaged, a switch located within the seatbelt buckle closes, allowing a positive signal to pass to the ECU. When the seatbelt is disengaged, the seatbelt switch remains open, and a ground signal is passed to the ECU. The TDSS interlock/monitor component takes advantage of this existing wiring running to the seatbelt by tapping into the wiring to read the voltage returning from the seatbelt switch to determine of the buckle is connected or disconnected.

Figure 5-5 below shows a basic circuit diagram of how the interlock component works. The information below is relevant to the installation of the interlock in the Infinity M45 test vehicle.

The interlock consists of a relay switch between the seatbelt wiring and the starter wiring, and a voltage buffer to prevent voltage drops along the seatbelt wiring. Both are installed underneath the dashboard at the ignition switch on the driver's side of the vehicle. The starter wire, which provides +12V when the ignition/key is in the start position, is interfaced with a normally open solid state relay. The relay switch (and thus the starter) is enabled by the seatbelt switch. When the seatbelt is engaged, the +12V (with reference to ground) across the seatbelt switch allows current to pass through the starter wire, and the vehicle can be started. When the seatbelt is disengaged, the relay remains open, and current is not allowed to pass through the starter wire preventing the vehicle from being started. A solid state relay was chosen because the relay draws a minimal amount of current compared to an electro-mechanical relay. However, due to the low current of the seatbelt signal, a voltage buffer was still installed to prevent voltage drops below +12V.

The voltage buffer (also called a voltage follower) was installed inline between the seatbelt wiring and the solid state relay. The voltage buffer simply consists of an op-amp and a dual polarity (+/-) 12V power source. A circuit diagram for the voltage buffer is shown in Figure 5-6. The voltage buffer is useful for this application because it has high input impedance, low output impedance, and a unity gain. Meaning, the op-amp does not draw much current, so the current running through the seatbelt wiring is protected, and the output voltage is maintained equal to the input voltage, thus preventing voltage drops. This was necessary because the current running through the seatbelt wiring was so low (~15mA), that the solid state relay drew too much current, causing a voltage drop along the seatbelt return wire. This voltage drop was significant enough (down to 6V) that the ECU registered the seatbelt as unbuckled even when it was actually buckled. Since air bag deployment uses seatbelt status information, it was necessary to correct this problem; this was accomplished by the voltage buffer.

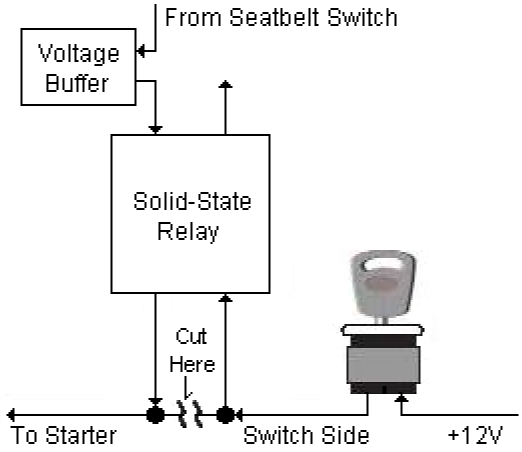

Figure 5-5: Interlock relay diagram

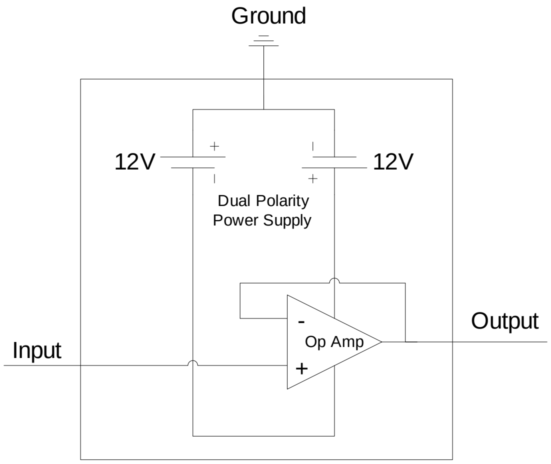

Figure 5-6: Voltage buffer diagram

In addition to the seatbelt interlock, the status of the seatbelt switch is monitored externally by the TDSS computer. Wiretaps are used to attach two external wires in parallel with the seatbelt switch wiring. The wiretaps are inserted beyond the seatbelt switch connector located on the lower right side of the driver seat. These external wires are connected to a DB-9 connector which can be attached to the TDSS computer's analog input port. This allows the TDSS computer to monitor the voltage supplied to the seatbelt switch while the vehicle is being operated. A measure of +12V indicates the seatbelt is engaged, while a measure of 0V indicates that the seatbelt has been disconnected.

There are perhaps several other methods to implement a seatbelt interlock, but this method was chosen because of its relative simplicity, low-cost, and permanence. Since installing the relay switch required the use of wiretaps and cutting of the vehicle ignition line, it could be considered to be somewhat invasive. However, this type of procedure is also simple enough that it could be carried out by a person who is capable of installing other aftermarket equipment such as a car stereo, or remote starter system. Since the installing of the interlock is semi-permanent, it may also deter an average user from disabling the system because it cannot simply be unplugged.

5.1.5 Fingerprint Reader

Figure 5-7 below shows a picture of the fingerprint module that was used in the TDSS system. Fingerprint readers have become more and more common in recent years, and they are finding their way into many commercial applications (e.g. many business oriented laptops on the market today) because they are a reliable method of identification. Although fingerprint readers can be purchased for relatively low cost, many of them are only compatible with Windows operating systems, and they do not offer a communication data protocol for third party developers. Some fingerprint identification system manufactures offer software development kits, but they are very expensive (thousands of dollars) when only purchasing a single unit. The fingerprint module for this project, the FIM10 manufactured by Nitgen, was chosen for its low cost, developers guide, and several other features.

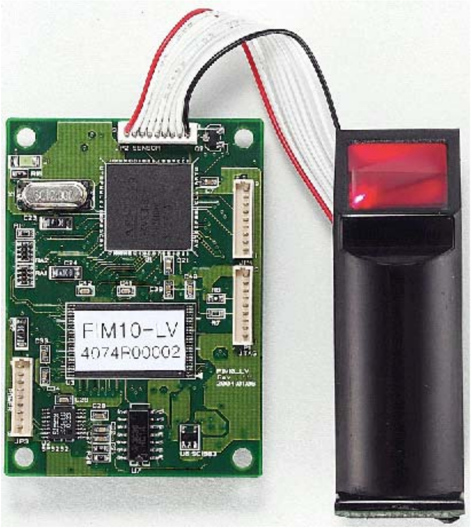

Figure 5-7: Biometric fingerprint module
(Nitgen FIM10)

In addition to the affordable price, the Nitgen FIM10 fingerprint module had all the necessary requirements for integration into the TDSS. The module was priced at around $150, which included the processor board, the fingerprint sensor, serial cable, and developers guide. Since the module contains its own processor and memory, it is a stand-alone device - similar to the other devices used with the TDSS. This means that the device does all of the processing for fingerprint identification, verification, and enrollment onboard using its own proprietary algorithms. This allows the fingerprint module to be added to any system with minimal development time and cost. The fingerprint module is then simply controlled by external communication from a host computer, such as the TDSS computer.

Using the communication protocol provided with the module, software was developed to communicate with the module via the TDSS computer's serial ports. Since RS-232 remains an industry standard and the other devices incorporated in the TDSS also comply with RS-232, it was logical to incorporate a fingerprint sensor that also used this standard. The TDSS computer is then responsible for initiating the identification procedure through the serial port, and the FIM10 module will return data through the same serial port.

Since the module is shipped as shown in Figure 5-8, an enclosure had to be built to house the sensor and processor board. An enclosure was built from a plastic case to protect both the processing board and the fingerprint sensor. A picture of the case is shown in section 8.1. The case also contains a DB-9 serial connector so the module can be connected to the TDSS computer using a standard serial cable. Since the device requires external power of +5V, the module was powered by +5V from provided by the TDSS computer through the same serial cable.

Another nice feature of the FIM10 fingerprint module was that in addition to the developers guide, it was also shipped with Windows software. The Windows software provided a simple graphical user-interface for testing, and enrolling fingerprints. Using this software, the fingerprints of the driver and supervisor were enrolled along with their identity and age on a home computer prior driving the vehicle. Since this software eliminated the need for performing fingerprint enrollment by the TDSS, the TDSS software was developed for the sole purpose of fingerprint identification. When the TDSS initiates the fingerprint identification procedure, it compares the scanned fingerprint to the database of previously enrolled fingerprints that have been saved to the systems memory. If a match is identified, the module returns both the name and age to the TDSS system where the age is subsequently checked and the information is logged in the driver report file.

5.1.6 Cellular Modem

The cellular modem used in the TDSS was the GPRS MultiModem manufactured by MultiTech, shown in Figure 5-8. The modem contains three external ports: one for the antenna, one for power (+12V), and a serial port for external communication. Like the fingerprint module, this device is a completely standalone unit. It also uses an industry standard communication protocol. Therefore it can be interfaced with just about any computer that can read a serial port with minimal development time. Once connected, the device is capable of providing wireless internet connectivity to the TDSS computer for data download and it also supports SMS communication.

Figure 5-8: Wireless cellular modem
(MultiTech GSM/GPRS MultiModem)

The modem allows real-time driver reports to be sent wirelessly in two different forms: a text message or an e-mail. For the case of sending SMS messages (also known as text messages) through the modem, communication is conducted through the serial port (connected at 9,600 baud rate) using the industry standard Attention (AT) commands. Table 5-2 below shows an example of what the AT command format looks like. The modem's SMS capability allows text messages to be sent to any digital phone that is capable of receiving an SMS message. The text messages are limited to a maximum of 160 characters, but this is sufficient to send enough information in the driver's reports generated by the TDSS.

The report e-mail is also sent through the modem in the form of an SMS message. Table 5-2 shows an example of the AT command format for sending an e-mail through the modem. The e-mail report can be sent to any valid e-mail address. As can be seen in Table 5-2, a similar CMGS command is sent, but this time the number "121" is used in place of the phone number. The number "121" is specific to the cellular provider, in this case Cingular, and is used to inform the provider's SMS server to route the message to an e-mail account instead of a telephone number.

Table 5-2: Example AT commands for sending text messages and e-mail reports

Text message	AT+CMGS = 6121234567 <CR> Example text goes here <ctrl-Z>
E-mail	AT+CMGS = 121 <CR> email@email.com(subject)body text goes here <ctrl-Z>

The modem is also capable of serving as a wireless internet connection for data download. This was accomplished through the same serial port, but using a different communication protocol – the Point-to-Point Protocol (PPP) – and connection speed (112,000 kbps). Since the communication protocol for text messaging and data download were different, these two processes could not be carried out at the same time on the same modem. A solution to this problem could be to stop and start communication to the modem only when it is required. However, since it can take minutes to establish a dial-in internet connection with the provider's wireless server, this may not be a very efficient procedure. For the demonstration of the TDSS, only one mode was used at a time. To demonstrate the SMS messaging capability, a permanent connection was established using the SMS software on the TDSS. To demonstrate the wireless download of weather data from the RWIS server, the SMS software was halted, the PPP connection was established, and the TDSS software that was responsible for downloading the weather data was started.

5.1.7 Audio Adaptor

To interface with the vehicle's audio system, the tape adapter shown in Figure 5-9 was used. The adapter plugs into the TDSS computer's stereo audio jack, and is inserted into the cassette player of the test vehicle. This allowed the TDSS computer to play feedback audio messages through the test vehicle's stereo, thus eliminating the need for a separate onboard speaker and amplifier. The TDSS computer contained an internal sound card, which was connected to the external audio stereo jack on the computer. Sound files were sent from the sound card through the cassette adapter to the car's cassette deck. Playing the sound files through the vehicle stereo's cassette deck allowed for sufficient amplification so the feedback messages could be heard.

There are also other possible methods to tie the feedback messages to the car's stereo. One such method would be to hardwire a connection to the stereo wiring so that the radio could be played while the feedback messages were not being played. This could be done by inserting a relay that switches between a stereo input and the TDSS computer input to the car's amplifier. However, this would require more permanent wiring. Since the TDSS was for demonstration purposes only, the method of using a cassette adapter was the least invasive, allowing the system to be conveniently removed when not in use. Also, what this solution did demonstrate was that future iterations of the TDSS could be incorporated into an aftermarket stereo system. This would allow complete control over how the stereo is used, so that in the event of a feedback message, the TDSS would have full control of the speakers. For demonstration, however, the cassette adapter worked well and required no modification to the vehicle.

Figure 5-9: Car stereo cassette adapter

5.1.8 Powering the System

To power the TDSS computer and external devices, two methods were employed. The first method powered the system directly from the vehicle's battery. For the demonstration set-up, the TDSS computer was located in the trunk of the test vehicle. Thus, power lines were run directly from the vehicle's battery under the hood to the trunk at the rear of the car. The power lines coming into the trunk of the car were fed into a switchbox (black box shown in the center of Figure 5-10), which contained a 25Amp fuse for surge protection, and switches for the fan and main power source. The main power line exited the switchbox and ran to a 3-way 12V car adapter (shown on the right side of Figure 5-10). Plugged into the 3-way adapter were the power cable for the cellular modem, the GPS receiver, and the computer; each of these devices requires a 12V power supply. The fingerprint module requires a 5V power source, so it was powered directly from the computer. Since the OBD-II port provides power from the vehicle, no external power source was necessary for the OBD-II adaptor. So, with the exception of the OBD-II adapter, all components of the TDSS were turned on and off by the main switch. One benefit of powering the system directly off the car's battery is that it is a continuous power source, so even when the vehicle is not running, the equipment can still be turned on and operated. This proved to be useful while debugging and testing the equipment when it wasn't necessary to have the vehicle running.

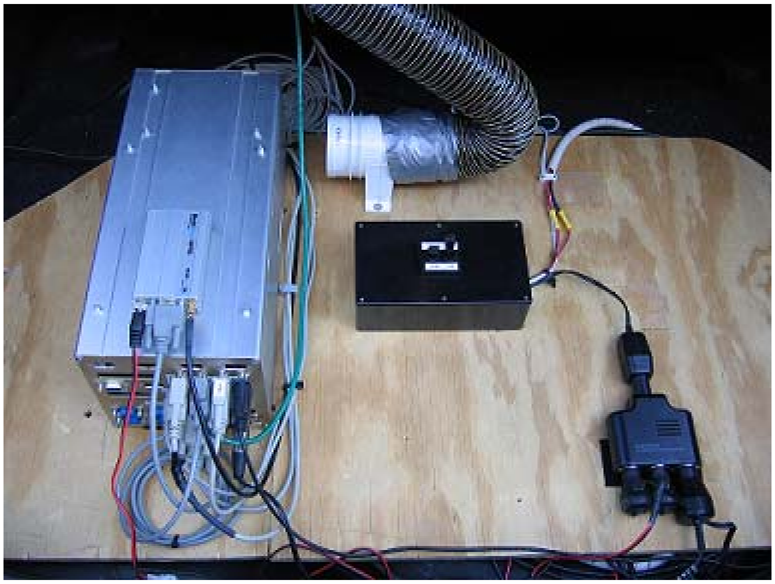

Figure 5-10: TDSS power set-up

The other method used to power the TDSS computer and the external devices was from one of the vehicles 12V (cigarette lighter) power sources located in the cab of the vehicle. In this situation, the 3-way car adapter was plugged into an extension cord that ran from the trunk of the car into the cab where it was plugged into one of the 12V sockets. The plug also had a switch, which allowed the system to be turned on and off from the inside of the vehicle. Similarly, all devices were powered from this single source, and all devices could be turned on and off from a single switch, with the exception of the OBD-II adapter. The only major difference in this method was that the 12V sockets inside the cab turn off when the vehicle is not running. Therefore, if the vehicle is turned off, the system will shut down. This method was used when it was convenient to turn the system on and off from inside of the vehicle, but the car remained running (this method was used while testing during the winter months).

6. The Digital Map: Incorporating Speed Data

6.1 Map selection

A digital map is an essential component of the TDSS. The map is used to provide both quantitative and qualitative information about the vehicle's current position, and enables the implementation of the ISA system. The GPS receiver provides a measure of absolute position, but this data is rather meaningless to both the user and the system without the map. Using the GPS position, it is possible to determine the location of the vehicle on a specific road so that the speed limit of that road segment can be determined, and the system can identify the possibility of upcoming curves. The map is also useful for the reporting component of the TDSS because the street location can be recorded which has more meaning to the user than the GPS coordinates.

There are essentially two sources of digital street map data that were considered for use in this project: commercial maps, and a publicly available basemap from the state DOT. To select a map source for this project, there were several considerations taken into account, and it was discovered that both map sources had trade-offs. However, in the end, it was determined that the publicly available map must be used, and the reasons why are outlined below.

6.1.1 Digital Map Overview

The basic structure of a road in a commercial or public map database is similar: roads are represented by lines and points. An entire street network consists of links, nodes, and shape points that are interconnected. Nodes are located at intersections or an endpoint where the road terminates. Links have a node at each end which represents the beginning point and end point of that segment. If the road section is straight enough, there road can be represented by a straight line segment defined by its two end points. If the road is not straight, or if it has some degree of curvature, the line segment will contain shape points. Shape points are used to represent changes in the road's geometry. Since the road segment is defined by its points, the road centerline is actually represented by the links connecting the points. An entire road is made up of one or more line segments (or links) which are often connected end to end. Thus, the basic representation of a road is piecewise linear, and it does not contain any arcs or more complex geometrical shapes other than lines. Also contained in the database are location and attribute information about each point. The point locations are often expressed in terms of a geographic coordinate system, and the attribute information gives details about the point, such as the name of the road the point belongs to. The road a particular line segment belongs to is defined by the attributes of the points it contains.

6.1.2 Commercial Maps

There are only a few select vendors of commercial map data, and these vendors provide map data in similar formats. The two primary suppliers of accurate street level digital map data are Navteq (www.navteq.com) and TeleAtlas (www.teleatlas.com). The data can be purchased in several commonly used formats, including the Geographic Data Files (GDF) format that is often used by car manufacturers. However, car manufacturers reformat the data into their own proprietary format, which is not publicly available. The GDF is also not a user friendly format as it requires fairly extensive knowledge of the formatting structure. Since many applications of digital maps require visualization of the map, formats that are compatible with current Geographic Information Service (GIS) software are also available. Most notably, the ESRI format is available for use with ArcView software. Data can also be requested from commercial vendors in an ASCII text format for custom applications. Selecting the format of the map data depends on the application for which the data is intended. Common applications include GIS, Computer Aided Drafting (CAD), and navigation systems.

Although a commercial map was not used in this project, commercial maps have advantages over public maps because they are updated more often and there is generally more attention to minimizing errors. Maps from TeleAtlas and Navteq are both updated four times a year. Commercial maps also have more attributes and data types in addition to streets, which is useful for commercial navigation systems that rely on a graphical interface to provide additional information to the user. Information such as points of interest, accurate addressing, and geographic boundaries are also contained in commercial databases. This information is not necessary for an ISA system, but is useful for route guidance calculations in commercial navigation systems. A reseller, American Digital Cartography, Inc., of both TeleAtlas and Navteq data has reviewed the primary differences between the two vendor's data (American Digital Cartography, 2006).

Speed limit attributes are also often included with commercial map data for the purposes of route calculation. However, this information is only an estimation based on the road classification and is not guaranteed to be accurate. For example, urban interstate highways may be generically assigned a speed limit of 55 miles per hour, but a given interstate could in reality have a speed limit of 60 miles per hour. Since an ISA system is dependant on the accuracy of the speed limit information, the speed limit attribute of commercial data is not sufficient for an ISA system. Additionally, the speed limit attribute is only associated with a given link, and does not reflect that actual location of the speed limit change, which often times occurs midway between two nodes along a link. These reasons, and the reasons described in the next section motivated the use of public map data.

A study by Cheng, Donath, Ma, Shekhar, and Buckeye (2005) showed that the public basemap data performed better than commercial data when matching GPS data to the correct street in the map. The state DOT basemap is created by digitizing 1:24,000 scale U.S. Geological Survey (USGS) quadrangles. This practice is used to create the Minnesota DOT basemap, and it is commonly used by other states to create their respective basemap. The map accuracy corresponding to a 1:24,000 scale map is 12.2 meters (40 feet), which is defined by the National Map Accuracy Standard (NMAS). The map accuracy of data from the commercial vendors is published as meeting the NMAS, and even exceeding this level of accuracy. Vendors of commercial data actually drive many roads to both verify and collect data. This procedure generally involves high accuracy GPS, and most often is completed in urban areas. Therefore, the accuracy in urban areas would be assumed to be better with the commercial data, and there is more attention to minimizing errors. TeleAtlas publishes a guaranteed accuracy of between 5 and 12 meters (TeleAtlas, 2006). The accuracy of Navteq data is comparable to TeleAtlas' data. Despite the published levels of accuracy by the vendors of commercial data, Cheng et al. found that the Mn/DOT basemap actually had a higher level of matching while using high accuracy GPS. This conclusion was made based on the results of a map matching analysis of 259.1 miles of roadway that produced 87% correct matches with the basemap and 73% with commercial map.

6.1.3 Public Maps

Despite some of the benefits of commercial map data, the publicly available map data from Mn/DOT was used for this project. Mn/DOT's map data was downloaded online via the Mn/DOT Office of Transportation Data & Analysis basemap website (www.dot.state.mn.us/tda/basemap/index.html). A benefit of using this data is that it is free to download. However, the map data is only available in an ERSI format because the basemap is generally used for GIS purposes. That meant that the data had to be converted to a format that would be compatible for use with the TDSS; this is discussed in detail in Chapter 6.3. Another drawback of this data is that it is not updated frequently, and is out of date by the standards of other map providers. At the writing of this thesis, the last update to the map on the basemap website occurred on 8/16/02, which was over 3 years ago. It is reasonable to assume, that a great number of changes to roadways have taken place since then. The map was suitable for the demonstrative purposes of this project, but the map does not meet the standards that would be required for a commercial system.

What makes the basemap unique over the commercial maps is that the map uses a Linear Reference System (LRS). An LRS is a method to define the location of street objects by a linearly measured distance along a given street with respect to the location of a reference point. This means that in addition to the coordinates of each map point, a distance attribute is also associated with each point. For the case of the Mn/DOT basemap, this distance was given as a milepoint location, so the units of measurement were given in miles. The milepoint locations of each map point can be thought of as an interpolation of the mile marker locations that exist along major highways, where the beginning of the road is at milepoint zero (0), and each node along the road is measured in miles with respect to the beginning. Figure 6-1 below shows the location of a speed limit sign measured along interstate I-94. The sign is located at 3.122, which is between mile markers 3 and 4, as shown.

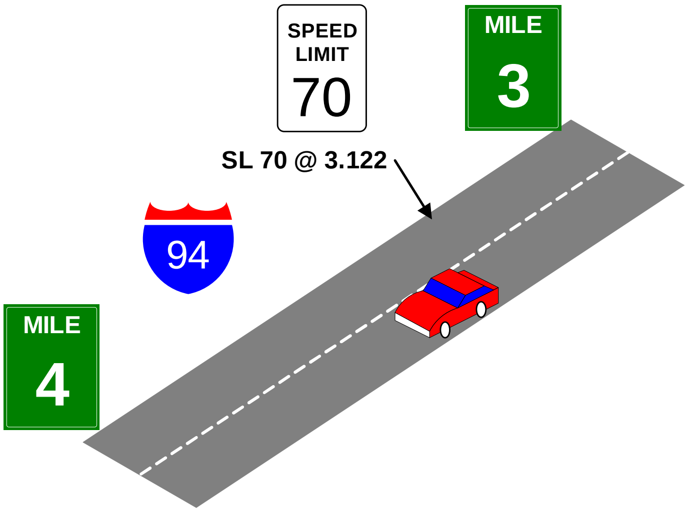

Figure 6-1: Example speed limit sign location using LRS

Commercially available map data only contains the global position of a node or shape point, and does not include distance measures of location with respect to a LRS. This was a major factor when deciding whether to use commercial map data versus the public map data. Since the speed limit data and curve speed data available were referenced with respect to the basemap's LRS, having the milepoint location of each node was necessary to determine the locations provided in the speed databases. If the speed and curve databases had also, or only, provided the coordinates of the speed data then the commercial maps may have been a more appropriate source of data. However, this was not the case since the speed data was measured with respect to the LRS used by the basemap, and only the road ID and milepoint location of the speed data was given. It is possible to determine the coordinates of the speed data from the milepoint location, but this would require using the basemap to do the necessary conversion. Therefore, the dependency on the basemap is still not eliminated. This fact, coupled with the other benefits of the basemap, and the idea that this data would be sufficient for demonstration purposes, made the basemap a logical source of data.

Using a LRS as a means of positioning does result in some inaccuracies. A report by NCHRP comments on the effects of using LRS data (Fekpe, Windholz, Beard, & Novak, 2003). Positioning using LRS is a common practice among state DOTs for locating objects, features, and attributes along a roadway. Specifically, there can be a loss of accuracy when using GPS and a map to determine the vehicle's linear location on the digital road map, especially when referencing the location of the vehicle with respect to location of another object along the roadway. For example, in the TDSS, the vehicle's distance location is compared to the location of the speed limit signs in order to determine the speed limit on the current road. An error arises because a continuous road network is being represented by discrete samples (data points) in the digital map, so actual curved sections of roadway are represented by straight lines. Therefore, in some cases the actual location of the vehicle may be some distance away *from* the map, but to estimate the vehicle's distance location, the vehicle must be placed *on* the map. Despite the accuracy of GPS, the vehicle's estimated map position is only as good as the accuracy of the map at that location. This can result in a sizeable loss in positional accuracy. This loss of accuracy then carries over to the distance estimation between the vehicle's current location relative to the speed limit sign location. Since the speed limit location was most likely measured using a Distance Measuring Instrument (DMI), the speed limit location is as accurate as the instrument used to measure the linear distance, and this distance is somewhat independent of the map. However, since the vehicle positioning relies on the map, determining the linear distance of the vehicle will result in errors cause by the map's inaccuracy. It should be noted that LRS data can have different levels of accuracy depending on the source of the data and how the milepoint location was measured. As discussed in NCHRP report (2003), a DMI has a typical accuracy of about +/- 1 foot per mile from the initial reference point.

There were some differences in the LRS data from each of the different sources. The basemap provides milepoint measurements at the nodes and points to three significant digits, or 0.001 mile. The speed limit data from Mn/DOT was the most extensive because it covered the entire state, and was also measured down to the three significant figures, or 0.001 mile. Hennepin county speed data and curve speed data from was only given to two significant figures, or 0.01 mile. Despite the differences in data measurements from the different sources of data, all the data was still referenced with respect to the basemap. Therefore, there was a direct correspondence between the speed data and the map.

6.1.4 Custom Maps

There is also a third type of map that was not considered for use in this project: custom maps. Generally these are maps that are created for specific research applications in limited geographic areas, and have been designed to support ITS vehicle technologies. One such map database has been developed at the University of Minnesota for intelligent vehicle applications (Newstrom, 2000). The geo-spatial database in this project was created by the University's Intelligent Vehicles Lab to provide map data to onboard ITS vehicle system. The spatial database includes high accuracy representations of real world geometry, including the roadway and the road features. A major difference between the geo-spatial database and the map data described in Chapter 6.1.2 and 6.1.3 is the representation of the road and level of detail. Commercial and public databases generally represent the road by a single centerline defined by nodes and links. The geo-spatial database uses accurately mapped spatial objects to define the entire road scene, which includes the centerline, lane boundaries, and shoulder. Using high accuracy GPS along with the geo-spatial database, it is then possible to determine the vehicle's position relative to the road with a high degree of accuracy. This information can then be used to determine if the vehicle is appropriately positioned on the road, or if a warning needs to be initiated because the vehicle has strayed from the roadway. The spatial representation of the roadway also enables the use of a Head-Up Display (HUD). The HUD is a visual representation of the roadway projected on a semitransparent "window" in front of the driver. Thus, it allows the driver to see a virtual representation of the roadway when the actual road markings are not clearly visible. The map data for the geospatial database is created by physically driving the roadway with high accuracy GPS to collect road feature information. Currently, the database only exists for a limited number of roads. To collect geo-spatial data (to a level of accuracy within 20 cm) for all roads in the entire United States, it has been estimated that it would take 200 vehicles approximately 3 years to complete (Trach, 2005).

A recent research mapping project called the Enhanced Digital Maps (EDMap) Project was initiated by the FHWA and NHTSA along with several automotive manufacturers (Ford, General Motors, DaimlerChrysler, and Toyota) and a commercial map vendor (Navteq) (Crash Avoidance Metrics Partnership, 2004). The goals of the project were to determine the accuracy and information required to support vehicle safety applications, along with the feasibility of making the map. The project outlined near-term, mid-term, and long-term EDMap databases, each with a greater degree of accuracy and information. Some of the map-aided (meaning they required the use of a digital map and would not be possible using sensor information alone) technologies that were demonstrated using sample near-term and mid-term map databases were curve speed assistant, stop sign assistant, forward collision warning, lane following assistant, and traffic signal assistant. These technologies were enabled by the EDMap because the map included information about road geometry, lane width, and sign locations to a high degree of accuracy. The near-term database would was specified to have 85% of its geometry within 2 meters, and 72% within 1 meter. The mid-term database had 96% of its geometry within 2 meters, 85% within 1 meter, and 51% within 30 cm.

The near term map included the potential for supporting the stop sign assistant, and relevant to this project were the curve speed assistant and a speed limit assistant. The EDMap report explains that current navigation databases contain speed ranges, but the near-term map would need to contain actual speed limit as a road attribute, and data collection though on-road mapping methods would be required to collect this information for inclusion. It was estimated that the near-term map could be completed in a year by driving all roads in the United States using 200 vehicles to collect data. As a comparison, it took Germany 12 to 18 months to create a speed limit database for the entire country. For an advisory system, the specified speed limit accuracy requirement for EDMap was 50 meters (note that this is within the current accuracy of the TDSS speed limit data). In the demonstrations of the speed limit advisory system, problems were reported because the system only registered the beginning of a speed limit zone, and did not contain speed limits for all road types. The project explains that Navteq is currently working to provide accurate speed limits on controlled access roads, interstates, and state highways.

Another vehicle safety research project that involved a research map provided by Navteq was conducted by UMTRI (2003). This project was the UMTRI lane departure project described in section 2.1.2 of this document. The map was referred to as the Advanced Driver Assistance System (ADAS) Product Set One (APSO). This map was created specifically for this project to meet the accuracy needs of implementing a road departure warning system that relied on a digital map, and the map was only generated for the region in which the field operational tests were to take place. The reason that a standard navigation map was not used was because the standard map data available from Navteq did not provide the accuracy necessary for predicting hazard potential based on calculated road curvature. As a result, the APSO map data was created as a supplement to the standard navigation map, but provided more precise road shape information to meet the needs of a curve speed warning subsystem, along with the other lane departure warning subsystems included in the UMTRI project.

6.2 Coordinate Conversion

The Mn/DOT basemap is provided in a projected coordinate system (represented using the GRS80 ellipsoid and NAD83 horizontal datum) using Universal Transverse Mercator (UTM)

Zone 15N. This means that the map data points were given in terms of a zone of coverage that was optimized for the entire state. To increase the accuracy in Hennepin County, the map data was converted to a local projected State Plane (Cartesian) coordinate system – Minnesota State South. As a result of the conversion, the map data maintained its units of measurement in meters. This was accomplished in ArcView using the *Projection Utility Wizard*. It should be noted that the TDSS software handled the conversion of the GPS data in real-time. Data provided by the GPS receiver is given in latitude/longitude, and was also projected to the Minnesota State South coordinate system. This portion of the TDSS software had been previously developed by the Intelligent Vehicles Lab at the University of Minnesota, and was reused for this project.

6.3 Map Formatting

Once the map source was chosen and projected to a local coordinate system, the next step was to convert the map data into a format useable by the TDSS. The downloaded map data was in the ESRI shapefile format suited for ArcView. Since ArcView is a visualization software package, the ESRI format uses the shapefiles (.shp file extension) for display of the map data. To convert from ArcView's shapefile format to an ASCII text file format, software was written using ArcView's Avenue scripting language. The software reads the shapefiles and converts the map data into text files for easier integration into to the database. The text files are formatted in a way that they can be copied to database tables in the database management system.

6.4 Map Database

The map files generated by the map formatting procedure represented a large amount of data that needed to be placed into a Database Management System (DBMS) for quick access and organization. To accomplish this, a database was created using PostgreSQL (www.postgresql.org). PostgreSQL was chosen for its performance, compatibility, and interface. PostgreSQL is an open source object relation database management system that is compatible with the QNX operating system running on the TDSS computer. (It is possible that MySQL, another DBMS, could also be used. When this project was started PostgreSQL was considered because it was available directly from QNX (www.qnx.com), so compatibility could be ensured. MySQL is also now available from QNX.) PostgreSQL is responsible for querying and returning map data within the TDSS software where it is further processed. In addition to the map data, the speed limit data, curve speed data, and weather data were also stored in the PostgreSQL database in their own respective tables. The interface allows queries to be made directly from the TDSS software written in the C programming language. The database also handled indexing of the data for optimal performance and query response. The data was indexed by PostgreSQL using the B-tree (an implementation of Lehman-Yao high-concurrency B-trees) strategy. The efficiency and speed of the PostgreSQL database allowed all queries and calculations on the returned data to be completed within the 1 second constraint defined by the GPS data rate.

The primary reason for converting the map to an ASCII text format was to allow seamless integration into the PostgreSQL DBMS. From the map data, three text files were created for conversion into database tables. The text files followed a similar format to a table, with a single entry representing a given point or road. Figure 6-2 below shows the data contained in each table of the digital map database. The tables created to store the speed limit data and curve speed data are shown in Figure 6-3. Figures 6-2 and 6-3 show the column names of each table, and the data type stored in the respective column. The map data table names were defined with a prefix to indicate the type of information contained in each table. The table with the ep- prefix contained position data for the end points (or nodes) of all road segments, the pts- table contained position data for all (nodes and shape points) of the segment's points, and the hwy- table contained details and attributes of each road segment.

Since PostgreSQL is a relational database, the map data in one table is referenced to the other tables by a unique ID number assigned to each road point. For example, if the ID number of a shape point is known, the street name of the road to which the shape point belongs to can be retrieved from the hwy- table using that ID number. The Transportation Information Service (TIS) code was also used to link tables. The TIS code is a unique number (created by Mn/DOT) used to identify a specific road (as opposed to the street name). The TIS code contains up to 11 characters; examples are shown in Tables 6-1 and 6-2. Included in the code are the road classification number, the county number, the municipality number, and the road number (e.g. from Table 6-2, 04 = County Highway, 27 = Hennepin, 05 = Highway 5). A road with a single TIS code can contain many links, each with points having their own ID. Therefore, the primary method to link map data tables was through the specific ID number of the points it contains. The TIS code was then used to determine the speed limit and upcoming curves from the tables in Figure 6-3. Chapter 7 gives some description of how the data in these tables was used by the TDSS software.

ep_henn	
id	integer
num_pts	integer
x_beg	integer
y_beg	integer
x_end	integer
y_end	integer

hwy_henn	
tis_code	varchar(12)
street_nam	varchar(30)
num_pts	integer
id	integer

pts_henn	
x_coord	integer
y_coord	integer
dist	real
id	integer
pt_num	integer

Figure 6-2: Digital map database tables

speed_henn	
tis_code	varchar(12)
beg_pt	real
end_pt	real
speed_limit	integer
description	varchar(70)

curve_csah15	
tis_code	varchar(12)
curve_id	integer
curve_dist	real
speed_limit	integer
curve_speed	integer
description	varchar(50)

Figure 6-3: Speed limit and curve speed database tables

6.5 Speed Limit Data

The speed limit data for this project came from two sources: Mn/DOT and Hennepin County. Unfortunately there is not a single organization that maintains speed limit data for the entire state. Each local road authority is responsible for setting the speed limits on the roads they maintain. Therefore, each road authority also has their own method of keeping track of speed limits. Fortunately, both Mn/DOT and Hennepin County maintain a spreadsheet of speed limit zone locations in a similar format - they both measure the locations with respect to the basemap's

LRS. It is possible that other road authorities in Minnesota also maintain data in a similar format, but it was discovered that the cities of Minneapolis, St. Paul, and Ramsey County do not. Therefore, the speed limit information from these authorities was not integrated into this project. Appendix F shows two maps of all the roads in Hennepin County that are contained in the TDSS speed limit database. The map in Appendix F, Figure F-1 shows the speed limits for Hennepin County roads. Note that the City of Minneapolis roads are not included in the county data because these roads are maintained by the city's own traffic authority. Hennepin County is responsible for the speed limit on all county highways and county roads. The map in Appendix F, Figure F-2 shows the speed limits for roads in Hennepin County maintained by Mn/DOT. Mn/DOT is responsible for speed limits on all interstate, state, and U.S. highways in Minnesota.

It may be possible to include an estimation of speed limits within the city of Minneapolis. Roads within the city limits are often set at statutory (MN Statute 169.14: Speed limits, zones; radar) speeds based on the classification of the road type. Therefore, roads could generically be assigned a speed limit based on the Mn/DOT's road classification with reasonable accuracy. However, a drawback to this method would be that the precise location of the speed limit signage would not be known. This method was not explored in this project, but could be investigated as part of a future effort.

The data from Mn/DOT and Hennepin County required a small amount of reformatting before it could be uploaded to the database. Although similar, the data did have some slight differences in formatting from each source, so the first task was to create a single uniform format so the data could be combined. Both sources supplied the speed limit data in a Microsoft Excel spreadsheet, which contained a sufficient amount of information to allow database integration. Each data source provided at least the road number, the begin and end point of the speed limit zone in terms of mileage along the road, the speed limit, and a text description of the speed zone referenced to landmarks. Table 6-1 represents a sample of the final format that was created for the speed limit data. Since only the road number of the Hennepin County roads was provided, the TIS code for these roads was created using the data format rules specified by the Mn/DOT basemap. Using the TIS code of the road allowed the speed limit data to be matched to the appropriate road in the map database because the map also used the road's TIS code for identification.

For the speed limit data, the locations of a speed limit zone corresponded to the real world locations of speed limit changes. The speed limit zone was defined by a beginning and ending location along a road. The speed limit was the same at any location in between the beginning and end of the zone. As can be seen in Table 6-1, the speed limit between 0.000 mi. and 3.122 mi. is 55 mph. Depending on the direction of travel, there is a different speed limit change on both sides of the highway at milepoint 3.122. This location represents the placement of a real world speed limit signs that indicates changes in speed limit. For example, for a vehicle heading in the direction of increasing mileage along I-94, a speed limit sign indicating a new speed limit of 70 mph would be located at milepoint 3.122. Heading in the opposite direction (the direction of decreasing mileage) along I-94, there would be a speed limit sign located at milepoint 3.122 indicating a speed limit of 55 mph. The TDSS used this same logic to notify the driver of speed limit changes, and also to determine if the vehicle speed was within the speed limit.

Table 6-1: Example of formatted speed limit data

TIS_CODE	BEGPT	ENDPT	LIMIT	DESCRIPTION
0100000094	0.000	3.122	55	MINN/N DAKOT SL TO BEG SL 70 .4 MI E MAIN AV/MRHD
0100000094	3.122	6.467	70	BEG SL 70 .4 MI E MAIN AV TO .4 MI E TH 336

6.6 Curve Speed Data

The curve speed data for this project was supplied by Hennepin County. Unfortunately the curve data from Hennepin County does not currently exist in a digital format. Instead, the information is contained in a log book of curve study sheets that are in paper format. The curve study sheets are a record of curve speed information for all curves on roads maintained by Hennepin County traffic engineers. For each road, the sheets indicate an appropriate advisory speed, the location of the curve, the signage type, and a text description of the location.

This information is gathered by traffic engineers through on-road driving and data collection. Section 6-6.06 of Minnesota's Traffic Engineering Manual (TEM) describes the method and procedure for determining advisory curve speeds (Mn/DOT, 2004). Traffic engineers use a method called the ball-bank test. The ball-bank test consists of a slope meter used to measure the centrifugal force on the vehicle while driving through the curve. The centrifugal force is based on the deflection of a steel ball inside a calibrated curve-shaped cylinder. Comfortable speeds are indicated by a deflection of less than 10 degrees. Traffic engineers drive the curve in both directions several times to determine a comfortable speed. If a comfortable speed is less than the speed limit for that section of road, then a cautionary curve arrow sign is used to mark the curve, and an advisory speed plate may also be used to indicate an appropriate speed for the curve.

The location of the curve on the curve study sheets is recorded as a linear distance along the section of the roadway. The reference point for each road corresponds to the reference location of the basemap, so the locations of the curves are described using the same LRS as the basemap. Instead of marking the location of the start of the curve, the location actually represents the middle, or center, of the curve. Using the center of the curve to define the location allows the curve location to be independent of the direction of travel along the road. However, it does not provide information about the start and end location of the curve, and unfortunately no information about the length of the curve was provided in the curve study sheets. A method for estimating the length of the curve is described in section 7.5.

For the purposes of demonstration and testing, only the curves along the demonstration route were included in the database. The information on the curve survey sheets were used to create a table of curve speed data for the demonstration road. Table 6-2 shows a sample of the data table that was created using the information provided by the curve sheets. The TIS code of the road was used to relate the roads in the curve speed table to the map data. The table also indicates the direction (left or right) of the curve based on whether the vehicle is driving in the direction of increasing or decreasing mileage along the road. This information was used to warn the driver of both the direction of the upcoming curve along with the appropriate advisory speed listed under the column labeled “CURVE.”

Table 6-2: Example of formatted curve speed data

TIS_CODE	ID	DIST	LIMIT	CURVE	INCR	DECR	DESCRIPTION
0427000005	1	0.81	35	30	R	L	At Fairchild Ave.
0427000005	2	1.04	35	35	L	R	50' E. of Tonkawood Rd.

7. The Software Methodology and Architecture

7.1 Software Selection

Choosing the appropriate software was a significant step in making the TDSS operational. However, the selection of software languages and packages were limited by several factors. Since previous development of software had taken place on other projects in the Intelligent Vehicles (IV) Lab, some software could be reused for this project. This was the primary consideration in choosing an operating system and programming language for the TDSS software. Prior development of software in the IV Lab involved the use of the QNX operating system, and software, such as the programs for GPS collection and inter-process communication (for communication between programs) had been developed in the C language. Using this core knowledge and building off the existing software, it was decided that the TDSS should also be programmed in the QNX environment, and all software should be developed in the C language.

7.2 Software Overview

Figure 7-1 below shows the software model of the TDSS. Each block represents an individual program within the software, and each rounded block represents a sensor. The TDSS software was broken down into three levels. The first level was responsible for data collection and communication with the external sensors of the TDSS. This information was then passed to either a secondary level program, called a module, or directly to the main program. In some cases, information from multiple sensors was passed to a module program. The purpose of the module programs was to preprocess the sensor data to determine the vehicle's current state, and to provide simplified information to the main program. At the third and final level was a single main program used to monitor the current state of the TDSS, and determine if the vehicle was being driving within the limits of safety defined within the system. The main program is also responsible for recording of driver data, and determining if a warning should be initiated, or a real-time report should be sent.

There are three secondary level programs within the TDSS software. The first is the map matching module, which is responsible for determining the vehicle's current location on a digital road map and the speed limit. The second is the curve speed module, which is responsible for determining if there is an upcoming curve, and if so, providing the details (e.g. advisory speed) of the curve to the main program. The third is the weather based speed module, which is responsible for determining a necessary speed reduction factor based on the current weather information. Each module is described in more detail in the following sections.

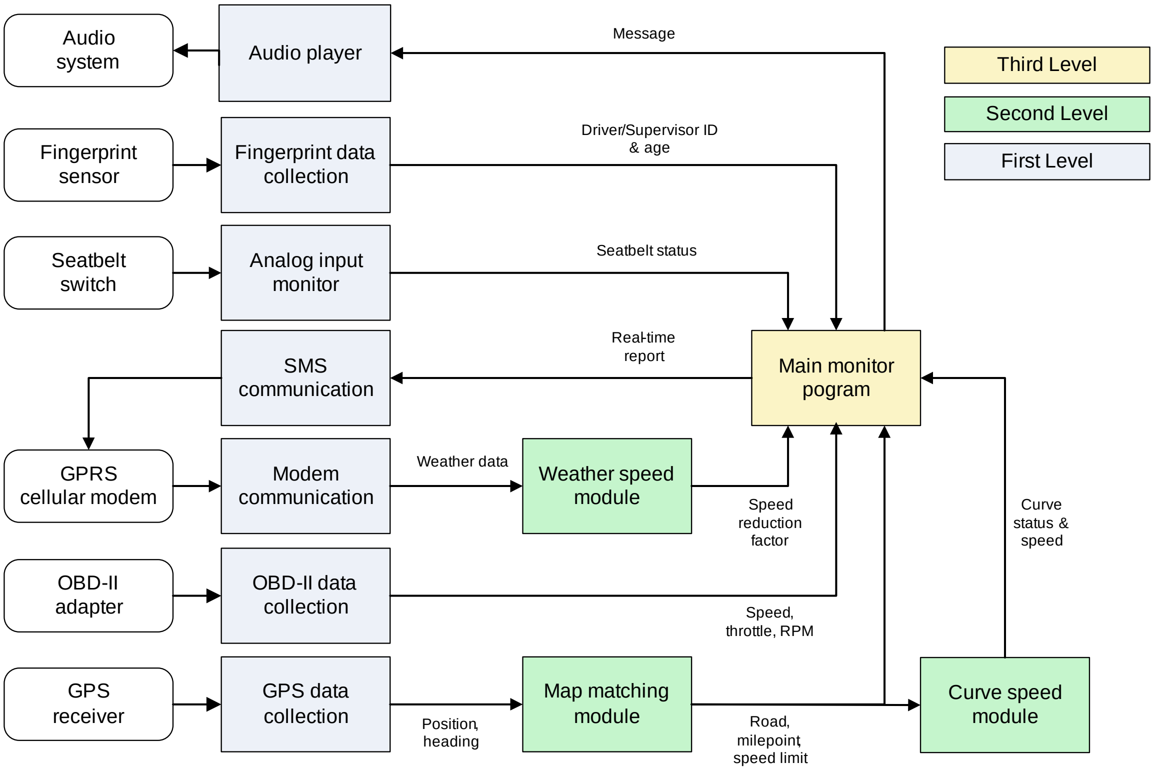

Figure 7-1: TDSS software data flow chart

The TDSS allows several parameters to be set internally within the main program. These parameters represented vehicle performance thresholds, and feedback responses were triggered when the threshold had been exceeded. For example, a maximum speed to trigger a real-time alert could be set at 80 mph. That means each time the vehicle exceeded 80 mph, a real-time report would be sent to the telephone number specified within the system. Table 7-1 below shows the parameters used for configuration of the TDSS and example values that were used during demonstrations.

Table 7-1: TDSS parameter thresholds in main program

Parameter Description	Example Value (Units)
Maximum speed threshold	80 (mph)
Speed differential threshold	10 (mph)
Absolute maximum RPM	3500
Throttle position range	30 – 70 (%)
Speeding time limit	30 – 60 (seconds)
Unbuckled time limit	30 – 60 (seconds)
Warning time limit	30 (seconds)
Max speed unbuckled	2 (mph)

The main program continuously monitored the vehicle state. If an infraction occurred, or if the system detected that the vehicle had exceeded one or more predefined thresholds, the information was logged to a report file. The main program generated a directory within the TDSS software directory. The directory was named using the current date so all log files created that day would be logged to that directory. The directory name was defined by the month, day and year and took the format of MO_DY_YR. The log files were placed within the current day's directory and were given a name using the time of day (hour, minute, second) the log file was created. The log files took the format of HR_MIN_SEC. The log files were a standard ASCII text file that could be downloaded from the TDSS computer and inputted into an Excel spreadsheet. The data fields in the text file were delimited using commas to allow logical placement of the data into the spreadsheet rows and columns.

A range of values is used for the thresholds on speeding time limit and unbuckled time limit. The warning time limit of 30 seconds was used so that the driver was first warned by an audible message if the driver was continuously speeding or was unbuckled for 30 seconds. The system used a random number generator to determine a maximum time limit threshold between 30 and 60 seconds. If the maximum time limit was reached, a real-time report was sent. A random number was used instead of a fixed number for the maximum threshold to prevent the driver from learning the time thresholds. If the driver knows when the real-time report is sent, then it is possible to prevent the report from being sent by keeping track of how long the infraction occurred, and correcting it just before the time limit is reached. By using a random number, the driver can not predict when a real-time report will be sent, and thus the best way to prevent the report from being sent is to drive without an infraction. All infractions are logged to the off-line report, so the driver can only prevent logging if they drive within the system's limits.

The TDSS is capable of monitoring simultaneous infractions, but uses a hierarchy to assign priority to the infractions. Infractions are listed from highest priority to least priority as follows: driver unbuckled, exceeding speed limit, exceeding curve speed, exceeding weather based speed, excessive acceleration. If two infractions were occurring simultaneously, the message for the highest priority infraction would be delivered first, and then the lower priority message(s) would be delivered subsequently if these infractions were still occurring. This ensured that the highest priority infractions were corrected first. However, if a lower priority message was being delivered, and the system subsequently detected a higher priority infraction, the system did not interrupt a message of lower priority to deliver a message of higher priority. Instead, they system would wait until the lower priority message was finished, and then deliver the high priority message.

7.3 Map Matching Module

There are a number of Map Matching (MM) procedures that have been documented (White, Bernstein, & Kornhauser, 2000; Bernstein & Kornhauser, 1996; Zhao, 1997; Quddus., Ochieng, Zhao, & Noland, 2003; Greenfeld, 2002; Zhou, 2004; Zhao, Quddus, Ochieng, & Noland, 2003). The basic MM methods have been defined by Bernstein and Kornhauser (1996), White et al. (2000), and Greenfeld (2002). In general, these methods involve the matching of position data derived from GPS to a physical location defined in a digital map (similar in structure to a map described in section 6.1.1). A paper by Quddus et al. (2003) summarized the map matching techniques described in these and other papers, and also provides information regarding the trade-offs of each technique. Quddus et al. (2003) and Zhao et al. (2003) also present a new improved MM technique that combines location data input from GPS and Dead Reckoning (DR) fusion using Kalman filtering, along with an empirical weighting method to determine the physical location on the link. Although somewhat outdated, a book by Yilin Zhao (1997) also gives a good general description of how navigation systems work, and also includes descriptions of the structure of some map databases and map matching algorithms.

In the TDSS, the positioning information was gathered from the stand-alone GPS receiver. Using additional information from other sensors, it is possible to improve the position estimate by means of sensor fusion. Sensor fusion combines the inputs from other navigation sensors, such as Inertial Measurement Units (IMU), rate gyros, digital compass to reduce the errors inherent to each sensor. A common method of sensor fusion for vehicle positioning is referred to as Kalman filtering (as in Zhao et al., 2003), but this technique was not used in this project. The TDSS did not include additional navigation sensors other than the GPS receiver. Speed information from the vehicle's computer (via the OBD-II port) could have been used to calculate a DR estimate that could be combined with the GPS data. However, it was determined that using the raw GPS position data provided a sufficient position estimate with minimal error in the MM result.

Since it was outside the scope of this project to develop an entirely new map-matching technique, the map matching procedure used for the TDSS was developed from a procedure described in White, Bernstein, and Kornhauser (2000), which can be described as a Heading Improved Point-to-Link (HIPL) algorithm. Similar to the HIPL algorithm, the TDSS map matching algorithm also matches the GPS position to the closest road link, and also uses heading information to improve the accuracy of the match. This procedure was chosen because of its relative simplicity and performance. As described in White et al. (2000), this type of map matching procedure has a higher percentage of correct matches than other more complicated procedures evaluated in this paper, such as matching the historical path of the vehicle to the road path, called a curve-to-curve algorithm.

Although the TDSS map matching algorithm performs well, some additional work was necessary to overcome the limitations of the point-to-link algorithm. Some measures to deal with these limitations were developed and included in the TDSS software, so in the end, the TDSS algorithm was really a modification of the point-to-link algorithm. The basic point-to-link algorithm does not take into account historical information of where the vehicle was previously matched. This means that every road within a certain distance of a GPS point is a candidate match after every position update. To improve computational efficiency and map matching reliability, the TDSS algorithm did take into account historical information. Specifically, the software used the previous match of the vehicle to limit the number of candidate road links. The candidate road links included the previously matched link, or links that were connected to the previous link. Only in the event that the system determined that the vehicle had left the road did the software include all candidate links within a certain distance. The processing sequence performed by the TDSS to determine a road match is shown in Figure 7-2.

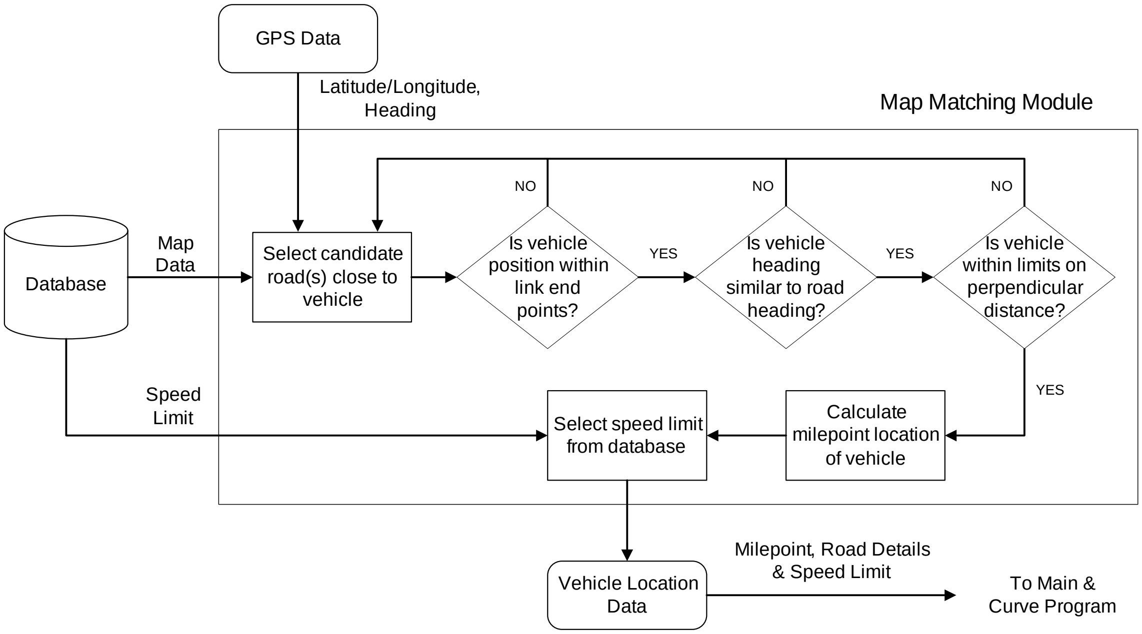

Figure 7-2: Map matching module sequence

As shown in Figure 7-2, the TDSS also included heading information to eliminate potential mismatches. Potential mismatches can occur with the point-to-link algorithm, especially near intersections. Since the algorithm attempts to find the closest link, errors can occur when the closest link is actually a road intersecting the current road, and not the current road. To reduce the probability of this error, intersecting roads can be eliminated as candidate roads by matching the heading of the candidate roads to the vehicle heading. To do this, the heading of a candidate road is calculated as the angle of the vector passing through the coordinates of the start point and end point of the road link. See Figure 7-3. Vehicle heading was calculated from the angle of the vector passing through the current and previous GPS coordinates. See Figure 7-4 for a diagram of vehicle heading. If the heading of a candidate road link is not within a tolerance (+/- 10 degrees was used within in the TDSS software) of the vehicle heading, the vehicle is not likely to be traveling along that road, and it is eliminated as a potential road. The actual road the vehicle is traveling on is selected as the match that meets this and other constraints. The actual road the vehicle is on must be within a certain perpendicular distance (10 meters was used within the TDSS software), the vehicle heading must be traveling along the direction of the road, and the vehicle position must be within the start and end point of the road link.

Once a map matching technique was developed, the difficulty of implementing the procedure was addressed. Despite the fact that many map matching techniques have been documented, there is no documentation regarding the implementation of a map matching procedure since the procedure is likely to vary from application to application and product to product. Therefore, a map matching procedure was developed specifically for implementation with the TDSS.

The goal of the MM procedure is to determine the position of the vehicle as a milepoint location $\mathbf{d_0}$ along a road in the digital map (using the LRS), as shown in Figure 7-3. The milepoint location was referenced to the location of the previous node along the given road link. An example of the position of the vehicle on the digital road map is represented in Figure 7-3 below. The vehicle's linear location, or milepoint, on the digital map can be though of as a linear interpolation between the milepoint of the previous and next points.

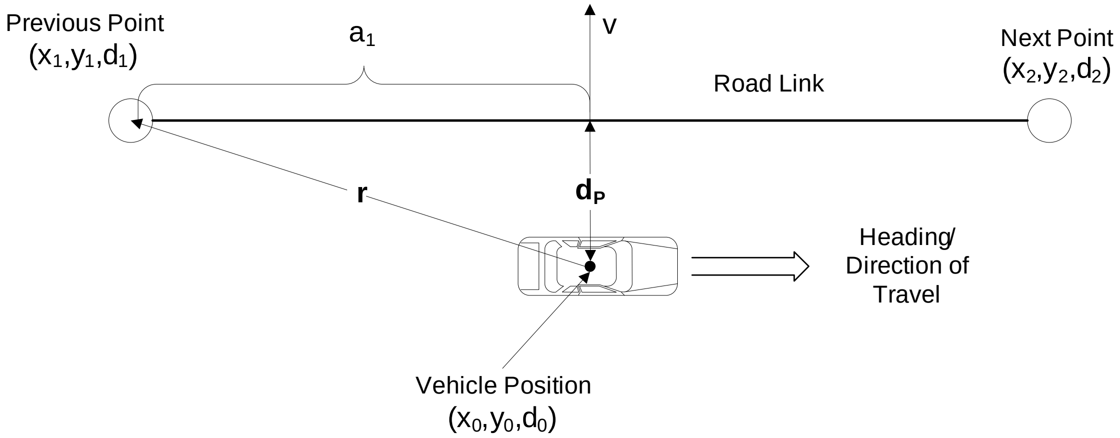

Figure 7-3: Vehicle with respect to the digital road map

The first step is to find the perpendicular distance $\mathbf{d_P}$ between the vehicle and the candidate road link that represents the actual road the vehicle is on. The perpendicular distance can be found by a vector projection of vector **r** onto **v**. As shown in Figure 7-3, vector **r** is the vector between the vehicle position and the previous point, and vector **v** is a normal to the road link and through the vehicle position. Equation 7.3-1 is used to calculate the perpendicular distance between the vehicle (x_0,y_0) and the road link using the coordinates of the previous (x_1,y_1) and next point (x_2,y_2). This value of $\mathbf{d_P}$ is also used to eliminate potential mismatches, and to determine if the vehicle has left the road map. If the perpendicular distance between the vehicle and the best matched road link is too large, it is likely that the road link is not a candidate match or the vehicle has left the road. In this case, the system either attempts to match another candidate road link, or discontinues matching until the vehicle has returned to a road contained in the map database.

$$d_P = \frac{|v \bullet r|}{|v|} = \frac{(y_2 - y_1)(x_1 - x_0) - (x_2 - x_1)(y_1 - y_0)}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}} \qquad \textbf{Equation 7.3-1}$$

Once the perpendicular distance is calculated, vector **r** - the distance between the vehicle position and the previous point - is calculated from equation 7.3-2. The magnitude of vector **r**, along with the perpendicular distance, is used to calculate the linear distance of the vehicle from the previous point along the road link. The distance along the road link from the previous point is given as $\mathbf{a_1}$ and is calculated using the Pythagorean Theorem as shown in equation 7.3-3.

$$r = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2} \qquad \textbf{Equation 7.3-2}$$

$$a_1 = \sqrt{r^2 - d_P^2} \qquad \textbf{Equation 7.3-3}$$

The milepoint location $\mathbf{d_0}$ of the vehicle can then be calculated using the location of the previous node along the given road link. The distance $\mathbf{a_1}$ (in miles) is added or subtracted from the milepoint location of the previous point $\mathbf{d_1}$, depending on whether the vehicle is heading in the direction of increasing or decreasing mileage, respectively. The milepoint location of the vehicle is computed using equation 7.3-4. The direction that the vehicle traveling is calculated using subsequent milepoint locations of the vehicle. If the milepoint location is increasing in value as the vehicle travels along the road, the vehicle is traveling in the direction of increasing mileage; if the milepoint location decreases in value, the vehicle is traveling in the direction of decreasing mileage.

$$d_0 = d_1 \pm a_1 \qquad \textbf{Equation 7.3-4}$$

Note, that this calculation of direction is different than the heading of the vehicle. The vehicle heading is the vehicle's angle of travel with respect to the Cartesian coordinate system with the Y-axis aligned with the direction of absolute North. The heading of the road link is calculated from the previous and next point along the link, and is given in equation 7.3-5. The atan2 function is used to calculate heading because it is a four-quadrant inverse tangent function, which measures the angle in radians from -π to π. The angle of the vehicle's heading was also measured using the same method. Figure 7-4 below shows a graphical depiction of the vehicle/road heading using atan2.

$$heading = a\tan2(d * (x_1 - x_2), d * (y_1 - y_2)) \qquad \textbf{Equation 7.3-5}$$

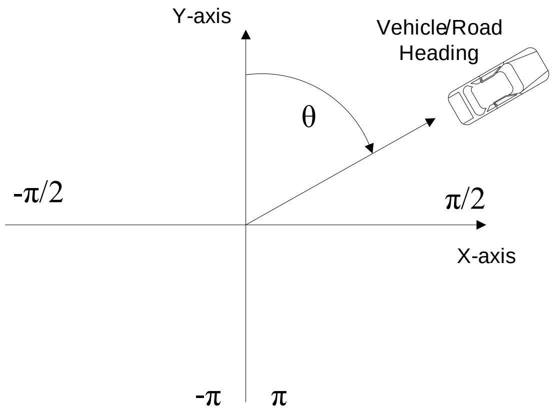

Figure 7-4: Depiction of vehicle heading

7.4 Determining Speed Limits

As a result of the MM procedure, a location estimate of the vehicle relative to the digital map is determined. The MM procedure provides the vehicle location as linear reference measurement of the vehicle along a road. More specifically, the milepoint of the vehicle and the TIS code of the road are determined. This information is all it takes to determine the posted speed limit at the current location. The sequence diagram shown in Figure 7-2 shows that the speed limit is determined at the last step of the MM module.

The database described in Chapter 6 includes the speed limit data that corresponds to the roads in digital map data. The map and speed limit data are both referenced with respect to the same LRS, but the speed data itself is not an actual attribute assigned to a node or link. Instead, the map data and speed limit data are contained in separate tables, and the speed limit is determined through a query of the speed limit database table using the TIS code and milepoint location. Keeping the speed limit data and map data separate is preferred over combining the data. A separate speed limit table allows updates to the speed limit data to be made independent of the map data. Thus, when a road's speed limit is changed, only speed limit data will need updating. In the situation where the road map needs to be updated to reflect changes to real world changes, both the map data and speed limit data will likely need updating.

As shown in Table 6-1 of section 6.5, the speed limit data includes the TIS code and milepoint location of the start and end of each speed zone along the road. The speed limit is determined by matching the TIS code of the current road to the TIS code in the speed limit table, and then finding the speed limit zone based on the current milepoint location. For example, if the vehicle is located at milepoint 4.243, the current speed limit would be 70 mph because the vehicle location is between the start (3.122 mi.) and end (6.467 mi.) location of the 70 mph zone. The milepoint location is recalculated after each GPS position update, and the speed limit is only updated if the vehicle leaves the current speed zone. Therefore, determining the speed limit does not require knowledge of the direction of the vehicle. So, if the vehicle location was eventually calculated to be 3.121, the vehicle would have entered a new speed limit zone, and the speed limit would be updated to 55 mph.

7.5 Curve Speed Module

A common method for implementing a curve warning system relies on the digital map as a "sensor" for determining the curvature of the upcoming road geometry. Based on the upcoming road curvature, an appropriate curve speed can then be estimated for safe curve negotiations. This type of system has a major limitation: the accuracy of the digital map must be sufficient to provide an appropriate estimation of curvature. Current commercially available digital maps do not provide the required level of accuracy for sufficient curve estimation. This issue was discussed in the EDMap project and the UMTRI projects. As a result, a higher accuracy digital map developed by Navteq was used by UMTRI, and new map requirements for a curve speed warning system have been specified in the EDMap report. Since the DOT basemap is close in accuracy to a commercial map, estimating road curvature using basemap data would also not be sufficient. The method of curve warning used by the TDSS was very different than the method used by UMTRI and others. Instead of estimating road curvature in real-time based on look-ahead calculations of curvature using the map, the TDSS system has prior knowledge of an appropriate curve speed contained in a curve speed database.

Given the format of the curve speed data, the location and advisory speed for each curve are known *a priori*. See Table 6-2 of section 6.6 for an example of the data contained the TDSS curve speed database. This method reduces the dependence of the system on the accuracy of the digital map. From the curve study sheets prepared by traffic engineers, the location of the curve is already known, as well as the advisory speed for each curve. Therefore, the map is not used to estimate an appropriate speed. Instead, the advisory curve speed in the database reflects the actual advisory curve speed that the traffic engineers have assigned to the curve. This means that the system warning will match the on road warning provided by the road signage.

There still exist drawbacks in using the curve speed data versus the map data as a source for curve position estimation. Since the curve speed data does not provide the required information about the length of the curve, the system still partially relies on the use of the digital map. A major benefit of using the map for curve estimation is that the system is not limited to locations where curve speed data has been collected. A system that relies on prior knowledge of the curve speed data would require that the data exists for all curves, and that the data is provided in a universal format.

The TDSS implementation of the curve warning module is shown in Figure 7-5 below. The software receives the milepoint and TIS code from the MM module, and uses this information along with the look-ahead distance to query the curve speed database to determine if a curve is located along the current road and within the look-ahead distance. The look-ahead distance is calculated by assuming that a 180° curve lies ahead so that the curve length calculation is maximized. Methods to calculate curve length, reaction distance, and brake distance are discussed below. Figure 7-6 shows the elements of the curve speed module. As shown, the look-ahead distance looks beyond the advanced warning distance so that the system can track the curve prior to arrival at the location where the warning is initiated. If a curve is not located within the look-ahead distance the system continues to monitor for curves upon each position update.

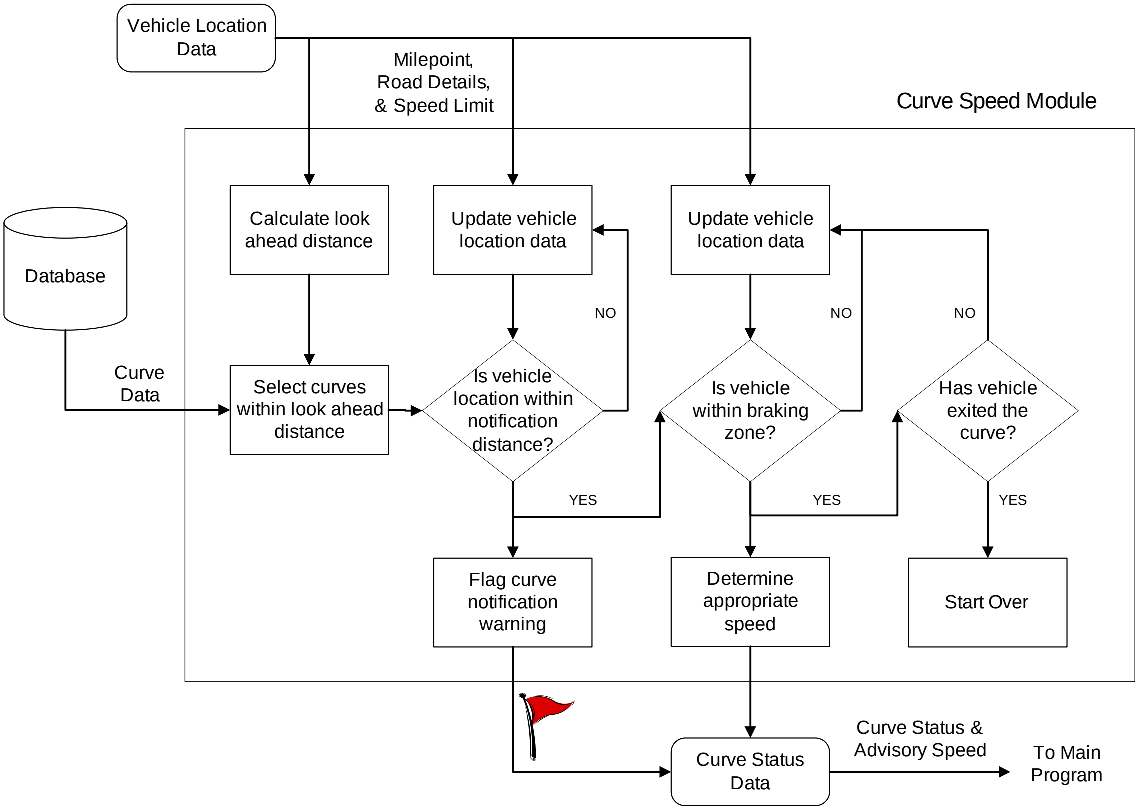

Figure 7-5: Curve speed module sequence

As discussed in Chapter 6, instead of marking the location of the start of the curve, the location actually represents the middle, or center of the curve. To provide appropriate feedback, the TDSS system must base warnings on where the upcoming curve starts because the start of the curve is the actual location where the advisory curve speed goes into effect. This means that the location where the curve starts must be determined. The starting location is estimated by adding or subtracting half the length of the curve to the center location of the curve, depending on the direction of travel. The starting location is shown schematically in Figure 7-6.

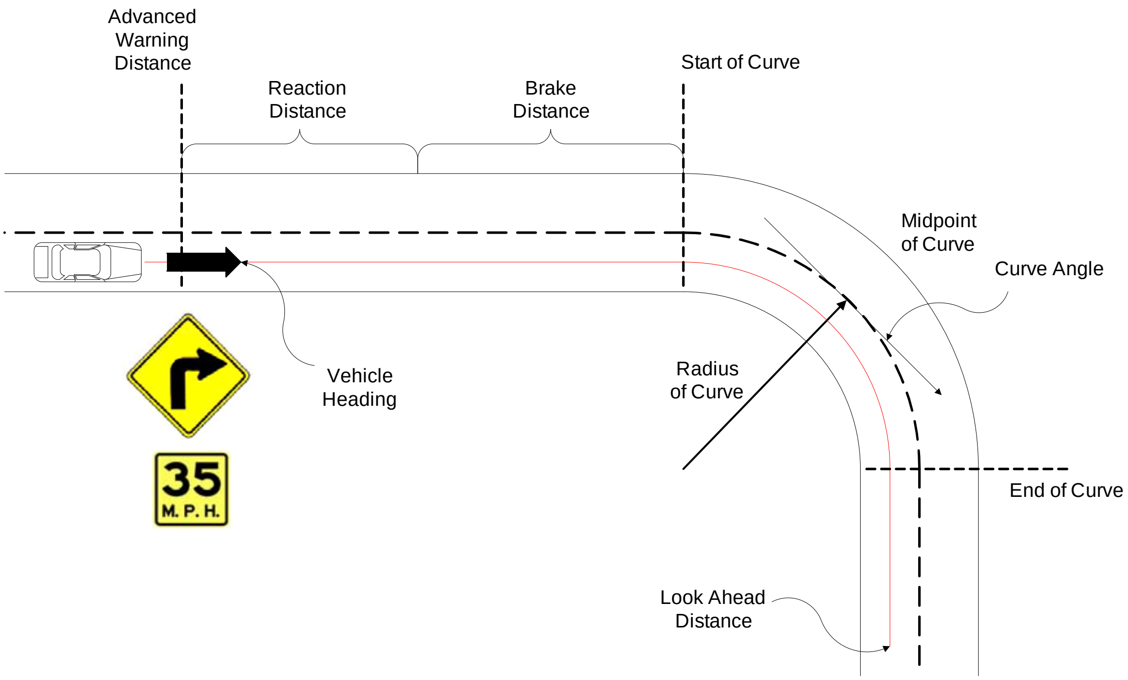

Figure 7-6: Curve speed elements

An estimate of the curve length was calculated using the digital map, along with road design guidelines used by traffic engineers. The Mn/DOT Road Design Manual (RDM) provides a method for determining advisory curve speed based on road curvature (Mn/DOT, 2004). This method is adapted from guidelines specified in the 2001 American Association of State Highway and Transportation Officials (AASHTO) "Green Book" (AASHTO, 2001). To calculate the length of the curve, the radius of curvature was first calculated using the known advisory curve speed $\mathbf{V_{curve}}$. Equation 7.5-1 was adapted from section 3-2.04 of the Mn/DOT RDM to calculate the radius of the curve $\mathbf{R_{curve}}$.

$$R_{curve} = \frac{V_{curve}^2}{15(e+f)}$$ **Equation 7.5-1**

This equation also requires knowledge of the road's superelevation **e**, or slope of the road, and the friction factor **f** of the road surface. The Mn/DOT RDM specifies a minimum superelevation of 0.02, and a maximum of 0.06. Since the superelevation of the road cannot be determined from prior knowledge, or within the capabilities of the TDSS, a value of 0.02 was used to provide a conservative result. With a lower superelevation, the curve radius estimate is larger, and thus a larger length is calculated because there is less estimated banking to the road. The friction factor **f** was calculated using estimation guidelines provided by the Mn/DOT RDM. The friction factor is linearly related to the speed of the vehicle, but there is a separate relationship below and above 50 mph. These relationships given in the RDM were created based on conservative values for friction factor derived from actual on-road tests. The friction factor was calculated using equation 7.5-2 or 7.5-3, depending on the speed **V** of the vehicle.

$$f = -0.001 * V + 0.19 \quad (V \le 50\text{mph})$$ **Equation 7.5-2**

$$f = -0.002 * V + 0.24 \text{ (V>50mph)} \qquad \textbf{Equation 7.5-3}$$

The map data was used to calculate an estimation of the curve length **s**. The curve length can be determined by using the equation of a circular arc, given in equation 7.5-4 below.

$$s = R_{curve} * \left|\theta_1 - \theta_2\right| \qquad \textbf{Equation 7.5-4}$$

Since the radius of the curve is known, the difference between the angle at the start of the curve θ_1 and the angle at the curve location θ_2 must be estimated from the map (in radians). This estimation was based on the difference between the heading of the vehicle prior to entering the curve, and the heading of the road at the midpoint, or halfway point, through the curve. The midpoint location is known from the curve database. The change in heading from the vehicle's heading prior to the curve, and the heading at the midpoint of the curve represents half of the curve's entire angular change between start and end. Half the angular change is calculated because the distance from the midpoint of the curve to the start of the curve is half of the curve's total length. Since this method to calculate the starting location relies on estimation of both the superelevation and angle of the curve, the result is also only an estimation that is as good as the accuracy of the superelevation and angle of curve. The angle θ_1 was determined based on the vehicle's heading. Then, the angle θ_2 was calculated using the map. The location of the curve was used to identify the road link that the curve was closest to, and the angle of the link was calculated from the arctan of the link's coordinates, along with the vehicle direction **d** (1 for increasing mileage, -1 for decreasing mileage), as shown in equation 7.5-5. The milepoint location of the start of the curve was calculated by subtracting or adding half the curve length to the milepoint location of the midpoint of the curve (remember the midpoint location was given in the curve study sheet), depending on whether the vehicle is heading in the direction of increasing mileage or decreasing mileage, respectively.

$$CurveAngle = atan2(d * (x_1 - x_2), d * (y_1 - y_2)) \qquad \textbf{Equation 7.5-5}$$

To provide the driver with an appropriate amount of time to prepare for the curve, the curve notification message was initiated prior to entering the curve. The notification location was determined using guidelines for advanced placement of warning signs found the Mn/DOT Manual on Uniform Traffic Control Devices (MUTCD) (Mn/DOT, 2005). These guidelines specify the location requirements for curve speed warning signs based on the speed differential between the speed limit and advisory curve speed. The distance is intended to adequately warn drivers with enough time to react and decelerate from the speed limit to the curve speed before the start of the curve. Table 2C-4 of the 2005 Mn/DOT MUTCD, which provides a guideline for determining advisory sign placement distance, is shown in Appendix G.

The TDSS used guidelines specified by the MUTCD for determining an appropriate warning distance. The warning distance is a combination of the reaction distance and the braking distance of the vehicle, as shown in Figure 7-6. The reaction distance $\mathbf{D_{react}}$ is calculated using equation 7.5-6 below with a reaction time ($\mathbf{t_{react}}$) of 2.5 seconds. The reaction distance is also dependant on the vehicle's speed **V**.

$$D_{react}(ft) = 1.47 * V(mi/hr) * t_{react}(s)$$ **Equation 7.5-6**

The braking distance **D_{brake}** is calculated using equation 7.5-7 below. The acceleration rate **a** is specified at $8.1 m/s^2$ (see Appendix G). The braking distance also depends on the vehicle's current speed **V** and the curve speed **V_{curve}**. The total warning distance is the sum of the reaction distance **D_{react}** and the braking distance **D_{brake}**.

$$D_{brake}(ft) = 1.075 * \left(\frac{V^2}{a} - \frac{V_{curve}^2}{a} \right)$$ **Equation 7.5-7**

The total warning distance is used to calculate the milepoint location where the curve notification message should be initiated. The milepoint location is determined by subtracting or adding the warning distance to the milepoint location of the start of the curve, depending on whether the vehicle is heading in the direction of increasing mileage or decreasing mileage, respectively. When the vehicle reaches this milepoint location along the current road, the TDSS notifies the driver of the direction of the curve and the advisory curve speed. Since the location of the notification is based on the driver's current speed, the advisory curve speed, and using conservative values for reaction time and deceleration rate, the driver should have sufficient time to slow down before the start of the curve.

Note that the latest release, the 5th edition, of the "Green Book" (AASHTO, 2004) has updated the methodology for determining superelevation and friction factor based on NCHRP Report 439 (Bonneson, 2000). Also, the results of a recent PhD dissertation titled *An Investigation of Comfortable Lateral Acceleration on Horizontal Curves* suggests that current design speeds for curves may be too slow because the methods to calculate side the friction factor are outdated (FHWA, 2006). These publications do not affect the methodology in the TDSS software that is described in this chapter. Current Mn/DOT practices were followed in this project because the TDSS was designed to match the real world road signage as closely as possible, and the 2004 Mn/DOT RDM is based on the 2001 release of the "Green Book." Additionally, the existing curve speeds provided in the Hennepin County database match the real world signs, and these advisory curve speeds are not based on these recent publications.

7.6 Weather Speed Module

The algorithms used by the TDSS to determine appropriate speed reduction based on weather conditions was based on a published report by FHWA (Goodwin, 2003). The report summarized the practices of 21 states' Department of Transportation (DOT) in using weather data to improve roadway operating conditions under inclement weather. In the case of several of these states, the weather data was used to dynamically set a safe travel speed (known as VSL) along certain sections of the highway. In many of these states, the weather data came from the respective state's RWIS, which is similar to the RWIS system in place in Minnesota. A summary of the states and their published algorithms for reducing speed limits or warning motorist is given in Table 7-2 and Table 7-3 below.

For the case of high wind, only the Montana and Nevada DOTs had a warning system in place; both were in the form of DMS that relayed a warning to the motorist. Both states had quantified a wind speed threshold for which the warning should be given, which is shown in Table 7-3. Since high profile vehicles are generally more affected by high wind, these warning messages were intended to target drivers of high profile vehicles. Additionally, the system did not reduce the speed limit in the case of high wind, it only issued a warning.

Based on the practices of these states, the TDSS system employs a similar strategy. Instead of reducing the speed limit, the system issues a warning to the driver in the case of high winds. The warnings are based on the practice of the Nevada DOT because their system takes both average wind speed and average wind gust data into account, but the warning messages in the TDSS have been modified. If the average wind speed is between 15 and 30 mph, or the average wind gust is between 20 and 40 mph, the TDSS issues the following warning message: “High wind potential.” If the average wind speed is above 30 mph, or the average wind gust is above 40 mph, the TDSS issues the following warning message: “Caution: wind advisory”.

Table 7-2: State DOT speed reduction based on visibility distance
(* includes other weather factors)

VISIBILITY	
ft(m)	Speed(mph)
Alabama DOT	
900 (274.3)	65
660 (201.2)	55
450 (137.2)	45
280 (85.3)	35
175 (53.3)	0
South Carolina DOT	
700 – 900 (213.4 – 274.3)	
450 – 700 (137.2 – 213.4)	45
300 – 450 (91.4 – 137.2)	35
Under 300 (91.4)	25
Tennessee DOT	
Above 1320 (402.3)	65
480 – 1320 (146.3 – 402.3)	50
240 – 480 (73.2 – 146.3)	35
Under 240 (73.2)	0
Utah DOT	
656 – 820 (200 – 250)	
492 – 656 (150 – 200)	50
328 – 492 (100-150)	40
197 – 328 (60-100)	30
Under 197 (60)	25
Washington DOT	
2640 (804.7)	65
1056 (321.9	55
528 (160.9)	45
528 (160.9)*	35

Table 7-3: State DOT warning messages based on wind speed
(* pertains to trucks)

WIND		
Ave. Speed (mph)	Ave. gust (mph)	Message
California DOT		
Above 35		High wind warning
Montana DOT		
20 – 39		Caution: watch for severe crosswinds
Above 39		Severe crosswinds: high profile units exit
Nevada DOT*		
15 – 30	20 – 40	High profile vehicles not advised
Above 30	Above 40	High profile vehicles prohibited

Looking at Table 7-2, five states have a quantified method for setting dynamic speed limits based on visibility distance. The dynamic speed limits were set along a single section of a single roadway, which had a fixed maximum speed limit for good weather conditions. The actual speed limit set along the section of roadway was determined based on the visibility distance reported from the weather sensors, and an appropriate speed limit was assigned to a visibility range.

Since the TDSS weather based VSL system must operate on all roads, where maximum posted speed limits change, the TDSS used a slightly different logic for speed reduction. The TDSS software did not directly employ a visibility-speed correlate used by a state DOT. For example, a visibility of 500ft would not always correspond to a set speed limit. Instead, the speed limit was set by a percentage reduction of the maximum posted speed limit along that stretch of road. This allowed for an appropriate speed adjustment for all roads, including those with different maximum speed limits. Roads with lower speed limits had a lower reduction, but the percentage by which the speed was reduced was always the same, and independent of the speed limit. Table 7-4 indicates the percentage reduction used by the TDSS. The percentage amount was determined based on the visibility range and percentage difference used by the Alabama DOT system. Additionally, the safe speed calculated by the TDSS was always rounded to the nearest 5 mph.

Table 7-4: TDSS speed reduction based on visibility distance

Visibility Range (ft)	Speed Reduction (%)
> 660	0%
450 - 660	15%
280 - 450	30%
< 280	45%

The TDSS includes other weather factors, in addition to the visibility, to determine a dynamic speed limit. The only DOT to publish the inclusion of additional weather information in their VSL system is the Washington DOT. The Washington DOT includes atmospheric (rain, snow, ice, etc) and surface conditions (wet, dry, icy, etc) and their associated severity. Since this information is also available from Minnesota's RWIS, this information was included in the TDSS weather speed algorithm. Similar to the method by which the speed was reduced based on the visibility distance, for the atmospheric and surface conditions, the TDSS algorithm reduces the speed limit based on a percentage of the maximum posted speed limit. The percentage reduction is also based on the severity of the condition. For atmospheric conditions, severity levels are described as heavy, moderate, light, slight, or none; for surface conditions the severity is determined by a measurement of the depth or as a percentage. Since there may be multiple types of inclement weather conditions, the TDSS determines which condition is most severe, and bases the reduction on that weather condition. Table 7-5 below shows a breakdown of the correlation between condition, severity, and percentage speed reduction. Refer to Minnesota's RWIS website (www.rwis.dot.state.mn.us) for a definition of terms. Again, the actual speed limit set by the TDSS was rounded to the nearest 5 mph. If no inclement weather conditions were reported, the speed limit remained at the maximum posted limit. New weather information is collected every 10 minutes, so the dynamic speed limit is only updated when new weather data is collected.

Table 7-5: TDSS speed reduction based on atmospheric condition

Weather Condition	Severity: Reduction (%)
Rain	Heavy: 15%
Snow	Heavy: 30%; Moderate: 15%
Mixed	Heavy: 30%; Moderate: 15%
Light Freezing	30%
Freezing Rain	45%
Sleet	15%
Hail	Heavy: 30%; Moderate: 15%
Frozen	Heavy: 30%; Moderate: 15%

Table 7-6: TDSS speed reduction based on surface condition

Weather Condition	Severity: Reduction (%)
Wet	Depth > 10mm: 15%
Black Ice	Coverage > 85%: 30%; 50 – 85%: 15%
Wet Below Freezing	15%
Ice Warning	45%
Ice Watch	15%
Snow Warning	Depth > 10mm: 30%; 0 – 10mm: 15%
Snow/Ice Warning	Depth > 10mm: 30%; 0 – 10mm: 15%
Chemical Wet	Depth > 10mm: 30% 0 – 10mm: 15%

7.6 Monitoring Acceleration

The TDSS monitored vehicle acceleration based on three parameters: the vehicle speed, engine RPM, and throttle position. This information was collected via the OBD-II port on the vehicle and monitored within the main program. In several of the commercial teen driver devices, thresholds are fixed for excessive throttle use and engine RPM. Therefore, feedback and recording are initiated each time this threshold is crossed. In the TDSS, a fixed parameter was used for the threshold on engine RPM and was statically defined within the TDSS software. However, the TDSS does not use a static threshold to monitor excessive throttle use.

The TDSS system dynamically sets a threshold for throttle position based on the vehicle speed. In general, throttle use and vehicle speed are not linearly related, so a second order relationship was created, which is shown in Figure 7-7. This method was created because it better accounts for the dynamics of the vehicle at varying speeds; accelerating from higher speeds requires more throttle because the vehicle transmission is operating in a higher gear.

A second order relationship between Throttle Position (TP) and vehicle speed **V** was given by equation 7.6-1. Solving for TP at the current speed gave a more appropriate threshold value for the maximum throttle position. The throttle position at 0 mph **TP_0** and at 70 mph **TP_{70}** defines the range of maximum throttle positions. The **TP_{70}** value is also the maximum throttle position at speeds above 70 mph (the maximum legal speed limit in Minnesota). Table 7-1 gives the range of throttle position values used by the TDSS. Figure 7-7 below shows the second order relationship between throttle position threshold and speed derived using equation 7.6-1 as a solid line. As shown, the throttle position threshold increases quickly at low speeds, but leveled off at higher speeds. A linear relationship is shown as the dashed line in Figure 7-7 for comparison.

$$\frac{TP_{70} - TP}{TP_{70} - TP_0} = \left(\frac{TP_{70} - V}{TP_{70} - 0} \right)^2 \qquad \textbf{Equation 7.6-1}$$

By monitoring throttle position and engine RPM, the TDSS is able to monitor the vehicle acceleration, and provides the driver with feedback during excessive acceleration. Although throttle position and engine RPM are related to vehicle acceleration, they do not provide an actual calculation of vehicle acceleration. If access to the vehicle's accelerometers (used in airbag systems) was possible, this information might provide a better measure of actual acceleration on which the monitoring could be based.

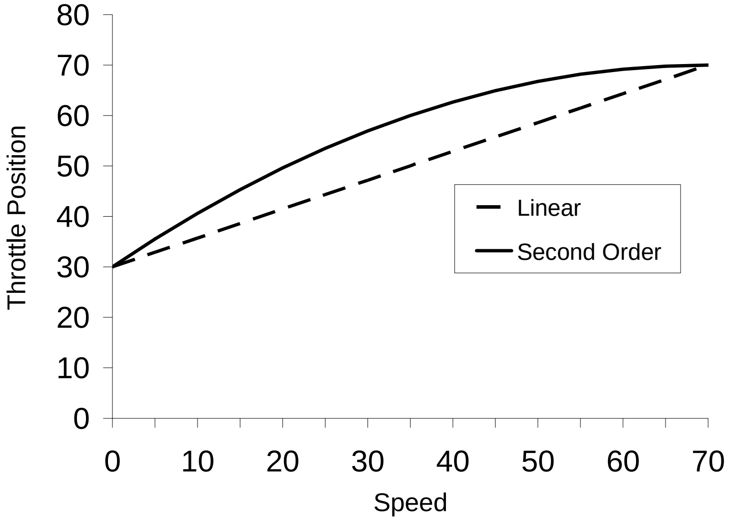

Figure 7-7: Calculated throttle position threshold as it varies according to vehicle speed using equation 7.6-1

8. Experimentation

8.1 Vehicle Setup Description

All evaluation and experimentation for this project was conducted using an Infinity model M45 sedan. The vehicle is shown in Figure 8-1 (a). The TDSS was designed so that it could be used in just about any passenger vehicle. With the exception of the seatbelt interlock/monitor, all components of the TDSS are removable; therefore, the TDSS can be moved to another vehicle without any great difficulty, and the components can be simply plugged in to the new vehicle. However, because this vehicle was predominantly used throughout the duration of the project, the setup shown was designed specifically for this vehicle. Therefore, the setup was optimized for user convenience during validation and demonstration.

The TDSS computer, which served as a hub for all external components, is housed in the trunk of the test vehicle as shown on the left side of Figure 8-1 (b),(c). As mentioned in Chapter 5, the computer was located in the trunk of the vehicle for convenience. In the experimental setup, a wooden board was used to provide a mounting surface to secure the computer, switchbox, fan, and power outlet, as shown in figure 8-1(c). The computer was secured to the board with Velcro so that it could be removed easily for servicing.

The TDSS sensors and external components are located throughout the vehicle, and all wiring leads to the trunk where the components plug into the front side of the computer. The cellular modem is attached to the top of the computer and powered from the 3-way 12V adapter in the trunk. The fingerprint reader shown in Figure 8-1 (d) is located on top of the center counsel between the front passenger seats. The GPS receiver is magnetically attached to the top of the trunk lid as shown in Figure 8-1 (e). The OBD-II reader plugs into the vehicle's diagnostic port as shown in Figure 8-1(f). The audio cassette adapter (not shown) wiring runs from the computer to the cassette player located on the center counsel. All wiring was routed in order to conceal as much of it as possible so that it didn't interfere with the driver or passengers during demonstrations.

(a) (b)

(b) (d)

(e) (f)

Figure 8-1: Vehicle experimental setup – (a) Infinity M45, (b) computer location in truck of vehicle, (c) close up of computer, (d) fingerprint sensor sits between front seats, (e) GPS receiver magnetically mounts on rear trunk lid, (f) OBD-II reader plugs into port underneath dashboard on driver's side

8.2 Route Description

Although testing and demonstrations were conducted on various roads in Hennepin County, the primary demonstration route is shown in Figure 8-2. This route began at the University of Minnesota and ended near Lake Minnetonka in Orono. The path runs from I-94 West to I-394 West to US 12 to Shoreline Drive (County State Aide Highway [CSAH] 15). The route terminates along CSAH 15 heading west near milepoint 8.36 where CSAH 15 intersects Shadywood Rd. In total, this route covers approximately 21 miles of roadway in one direction.

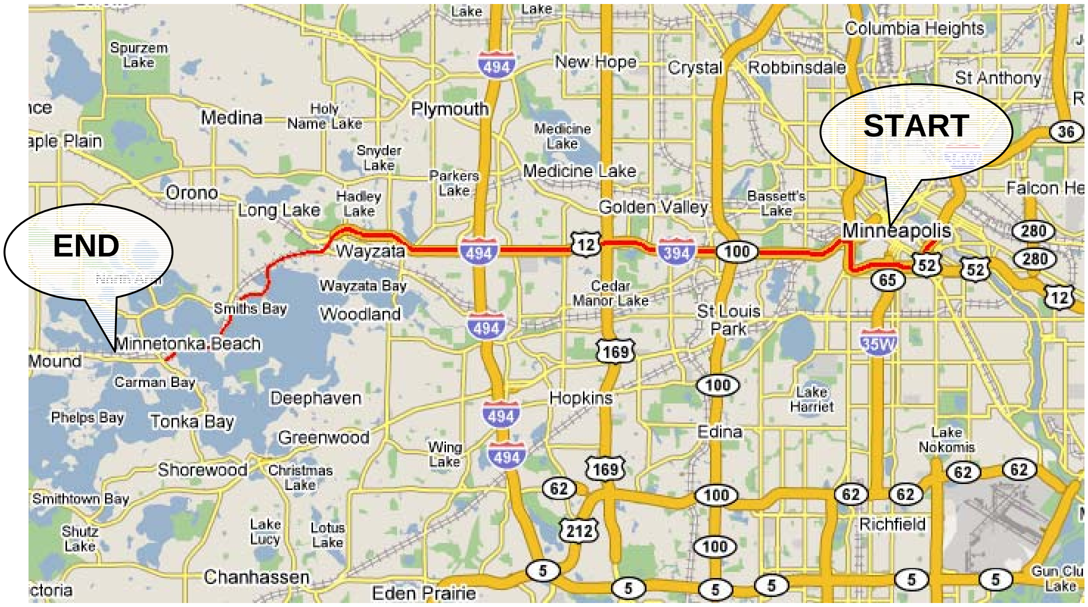

Figure 8-2: Demonstration route – shown in red between start and end arrows (Photo source: maps.google.com)

This route was chosen because it provided a variety of features in which the TDSS system could be tested. The route included segments of divided interstate highways and two-lane county highways. The primary influence that defined the route was the inclusion of CSAH 15. CSAH 15 was chosen as the best route to test the functionality of the curve speed warning system. This road was suggested by Hennepin County transportation engineers because it has a high density of curves; the section of CSAH 15 included in the demonstration route has a total of 14 curves included in the database. Table H-1 of Appendix H lists information about the curves such as the advisory speed, curve direction (when heading in direction of increasing or decreasing mileage), and milepoint location.

This route also has several speed limit changes, which meant that the capability of the system to recognize these speed limit changes could be tested. Speed limits for the city of Minneapolis were not included since the Hennepin County database began outside the city limits. The speed limit feedback component was always operating, but did not begin to notify the driver of speed limits and speed limit changes until the vehicle entered I-94 West (the first road along the test route in the speed limit database). The speed limit segments along the entire route are given in Table H-2 of Appendix H. In some cases the speed limit zones are staggered (along CSAH 15), meaning that speed limit zones do not start at the same milepoint location along opposite sides of the roadway. In situations where staggered speed limit zones occurred, the zones between the staggered signs were assigned a speed limit of 0 mph. When the vehicle entered a zone where the speed limit was 0 mph, the TDSS could then recognize that it had entered a staggered zone and would set the speed limit to the value of the next zone. This method works for both directions of travel along the roadway.

Since there are also several road changes along the test route, the functionality of the map matching algorithm could be verified. There are four road exchanges along the test route, and the system was developed to recognize road changes and notify the driver of the new road's speed limit. The long stretch of interstate highway along I-394 also provided a sufficient length of roadway to test the other components of the TDSS. The speed limit monitor, seatbelt monitor, weather monitor, and text messaging components could be verified and demonstrated. For example, the speed limit along this stretch is 55 mph, so if the vehicle were to exceed 55 mph, the system would warn the driver. If the driver continued to speed beyond the allowed time threshold, or if the driver exceeded 10 mph above the speed limit, a text message would be sent and received on a cell phone (located in the vehicle for test purposes). The system was also tested in the situation where multiple infractions were occurring simultaneously. The system was designed to be capable of monitoring all infractions continuously, so if the driver were to speed above the speed limit and disengage their seatbelt, the system would record and warn the driver of both infractions.

8.3 Experimental Description

In addition to the observational validation of the TDSS, an experiment was conducted to evaluate the difference in speed data collected via the OBD-II port on the vehicle and the GPS receiver. There was some discrepancy between the information collected from the OBD-II, the GPS receiver, and through visual observation of the speedometer. Therefore, the variation of speed between GPS and the OBD-II was tested. A description of the experiment is provided below, and the results are documented in Chapter 9. More information on the observational results of the system is also described in Chapter 9.

8.3.1 Experiment: OBD-II Evaluation

The purpose of this experiment was to compare the vehicle speed data collected from the vehicle's speed sensor (via the OBD-II data bus) versus speed calculated using GPS. From this comparison conclusions can then be made about which data source is recommended for use with the TDSS. The OBD-II provides access to the vehicle's speed sensor, which is the vehicle's own internal measure of the speed the vehicle is traveling. The GPS speed is determined by calculating the distance (in meters) between successive position data points and dividing that distance by the time between position updates (1 second). The calculated value is then converted from meters per second to miles per hour. The GPS receiver provides position updates at a rate of 1 Hz, so GPS speed could be calculated at a maximum rate of once per second. Since the data collection rate was limited by the GPS receiver, data was collected simultaneously from the OBD-II port and GPS once per second. Speed data from the OBD-II port and GPS receiver were also collected in 1 mph increments (zero significant digits).

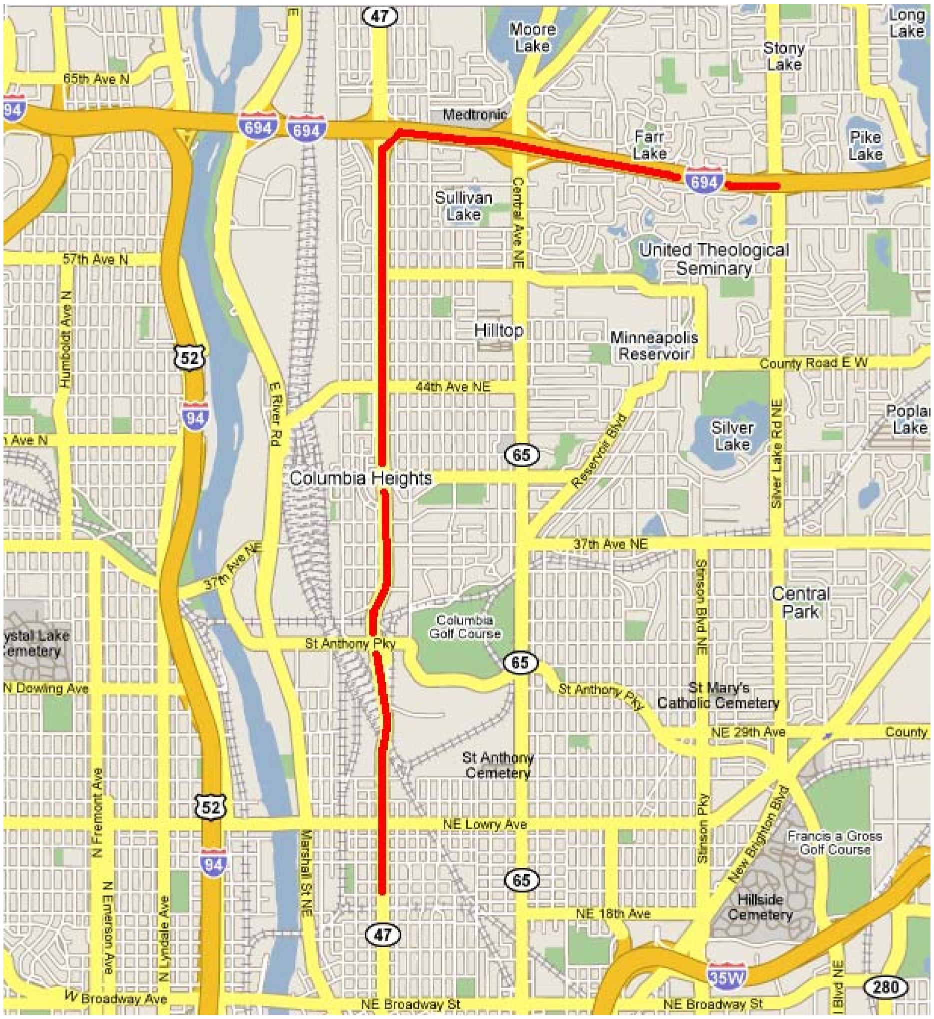

Figure 8-3: OBD-II test route – shown in red
(Photo source: maps.google.com)

The experiment was performed using six vehicles of different manufacturers (Ford, Chrysler, General Motors, and Import (Infinity and Volkswagen)) to get a cross-manufacturer and vehicle comparison. Table 8-1 shows a list of each vehicle used in the experiment. The experiment was conducted at speeds between 0 and approximately 65 mph along University Avenue (Hwy 47) and Interstate I-694. Data was collected in both directions using each vehicle. The test route was the same for each vehicle, and the route was approximately 6.4 miles in each direction. Figure 8-3 shows the route used, which starts in Minneapolis on University Avenue and 19th Ave. NE, and ends in Fridley at I-694 and Silver Lake Road. During all runs, the vehicle was driven in prevailing traffic conditions to collect data that reflects real-world driving situations. The test also included several stop and start situations so that data could be collected while the vehicle was accelerating and decelerating. Results of GPS calculated speed versus OBD-II speed are described in Chapter 9.

Table 8-1: Vehicles used in OBD-II evaluation experiments

Vehicle 1	2003 Infinity M45
Vehicle 2	1998 Ford Ranger
Vehicle 3	1999 Dodge Stratus
Vehicle 4	2001 Chevrolet Malibu
Vehicle 5	1997 Volkswagen Jetta
Vehicle 6	2002 Chevrolet Venture

9. Results

9.1 Experimental Results

Table 9-1 below shows the results of an analysis comparing speed data collected using GPS versus the vehicle's speed sensor. The speed data collected from the vehicle's speed sensor is referred to as the OBD-II speed because it is collected via the OBD-II port. Figures 9-1 to 9-6 provide a histogram of the difference in speed for each data sample collected from each vehicle during each trial run. The histogram is used to show the distribution of differences.

For each run, data outliers were thrown out. In several instances, the GPS measured speed was close to 0 mph even when the vehicle was traveling at high speeds. This caused a large difference in the calculated difference between the OBD-II speed and GPS speed. These numbers were removed prior to the data analysis, but it should be noted that some inconsistency was observed in the GPS data in these instances. This is not a large reason for concern because this type of error could be filtered out within the software.

Table 9-1 shows the results of an analysis on the difference between the speed data collected from the OBD-II versus GPS calculated speed. Table 9-1 provides the number of data samples collected, the maximum and minimum difference between the OBD-II and GPS speed, the mean difference, and the standard deviation of the difference during each trial run using each vehicle. The standard deviation is used to provide a measure of the spread of the difference. The mean difference is the average difference between the measured OBD-II speed and calculated GPS speed during each run and shows whether the difference had a positive (OBD-II speed > GPS speed) or negative (OBD-II speed < GPS speed) tendency.

Table 9-1 does show consistency in results for each vehicle, but results between vehicles varied slightly. Looking at Table 9-1, the values of mean difference for each vehicle was consistent in that the result for runs 1 and 2 were both either positive or negative. Since the difference was calculated as the value of OBD-II speed minus the GPS speed, a negative mean difference meant that the OBD-II was slightly higher on average, and vice versa. The mean difference was not significant for most vehicles; the mean difference for all vehicles except Vehicle 1 is less than 1mph. However, as shown in Table 9.1, there is a larger average discrepancy between the OBD-II and GPS speed collected using Vehicle 1 compared to the other vehicles. The mean differences between the OBD-II speed and GPS speed is -1.61 and -1.48 for runs 1 and 2, respectively. An observation of the vehicle's speedometer during tests appears to differ from the OBD-II speed by about 2 mph, which is close to the -1.61 and -1.48 difference calculated. Looking at the histogram in Figure 9-1, the greatest number of sample differences calculated were -2 mph, which is also consistent with this observation. This would most likely indicate that the speed data collected from the OBD-II of Vehicle 1 is not calibrated correctly. The average difference for all other vehicles does not exceed an absolute value of 0.57 (Vehicle 6, run 2). Looking at the histograms for all other vehicles the greatest number of sample differences is generally 0 mph. This would suggest that the OBD-II calibration is fairly accurate.

Table 9-1 also shows that there can sometimes be a large difference between the OBD-II and GPS speed data, as indicated in the minimum and maximum difference columns. Although large maximums (11mph) and minimums (-8mph) were observed, as in Vehicle 4, run 2 (Table 9-1), they did not occur with great frequency. Figure 9-4 shows that values of large difference did not occur many times during each trip. This is reinforced by the low standard deviation values calculated in Table 9-1, which are all less than 2 mph. These values of maximum difference generally occurred during accelerations and decelerations. Large positive (local maximum) differences also generally occurred during deceleration (periods the vehicle speed was increasing), while large negative (local minimum) differences generally occurred during accelerations (periods when the vehicle speed was decreasing). Reasons why this may have occurred are described below.

Figures 9-4 and 9-5 show example acceleration/deceleration profiles for Vehicle 4 and Vehicle 6, respectively. As shown in these figures, there is a “lagging” trend observed in the GPS data behind the OBD-II speed data. This means that upon acceleration, the GPS speed data is generally lower than the OBD-II data. The opposite is true during deceleration - the GPS speed is generally higher than the OBD-II data. When the vehicle has reached a steady state speed, the data is generally in closer agreement. Since a large portion of the driving time is at a relatively steady state speed, the OBD-II and GPS speed are often in agreement, which would explain why the histograms show a large number of sample differences of 0 mph.

The cause for this lag effect is likely to be due to the nature by which the speed is calculated using GPS. Since the speed is calculated using position updates at one second increments, the speed that is calculated is actually the *average* speed between position updates. If the vehicle is accelerating during the position update, the calculated vehicle speed is an average of the current speed and the speed during the previous position update. Therefore, the calculated speed will be some value in between the current speed and the previous speed, but less than the current speed because the previous speed is less than the current speed during acceleration. The opposite is true during deceleration. The calculated speed will be higher than the current speed because the previous speed is higher than the current speed, and calculated speed is the average of the current speed and the previous speed.

From the analysis of the data comparing OBD-II and GPS speed, it can be determined that both may be a reliable source of speed data. The reason is that despite the observed lagging effect of the calculated GPS speed during acceleration and deceleration, the values quickly came into agreement once a steady state speed was established. Since most driving is likely to occur at steady state, the data would suggest that both sources are generally in close agreement, as shown in Figure 9-8. However, it should be noted there are some limitations to each source of data. If the calibration of the OBD-II speed is off, as in the case of Vehicle 1, then the speed will be slightly biased high or low. If the bias exceeds a couple of miles per hour, the difference could lead to too many or too few warnings to the driver, depending on the direction bias (high or low). If the bias were high, this may not be acceptable to the driver, who could become frustrated with the system if it was providing warnings when the driver wasn’t speeding. If the bias was low, the system could loose effectiveness if the driver could exceed the speed limit without being warned. One advantage of GPS is that will not be consistently biased, only during acceleration and deceleration. However, if no bias is observed from the vehicle’s OBD-II speed, it is a better source of speed data because there is no lag effect in this sensor. Additionally, GPS is also subject to loss of signal in urban canyons and tunnels, but the OBD-II is not affected by such.

Table 9-1: Analysis of speed data collected from vehicles used in OBD-II evaluation

Vehicle	Run	Number of Data Samples	Maximum Difference (mph)	Minimum Difference (mph)	Mean Difference (mph)	Standard Deviation (mph)
Vehicle 1	1	494	3	-5	-1.61	0.93
	2	639	4	-7	-1.48	1.32
Vehicle 2	1	548	6	-5	-0.13	1.17
	2	553	6	-5	-0.19	1.23
Vehicle 3	1	596	5	-5	0.14	1.10
	2	665	6	-5	0.17	1.13
Vehicle 4	1	661	6	-6	-0.38	1.72
	2	594	11	-8	-0.53	1.66
Vehicle 5	1	593	3	-5	0.23	0.90
	2	643	6	-7	0.12	1.13
Vehicle 6	1	684	4	-6	-0.29	1.22
	2	608	7	-8	-0.57	1.68

Figures 9-1 through 9-6 below are histograms showing frequency of calculated difference between OBD-II and GPS speed data for Vehicles 1 through 6, respectively.

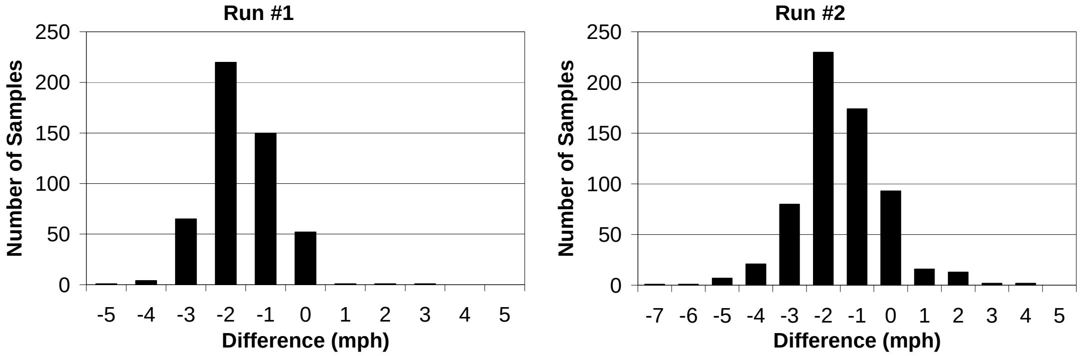

Figure 9-1: Vehicle 1 (2003 Infinity M45), runs 1 & 2

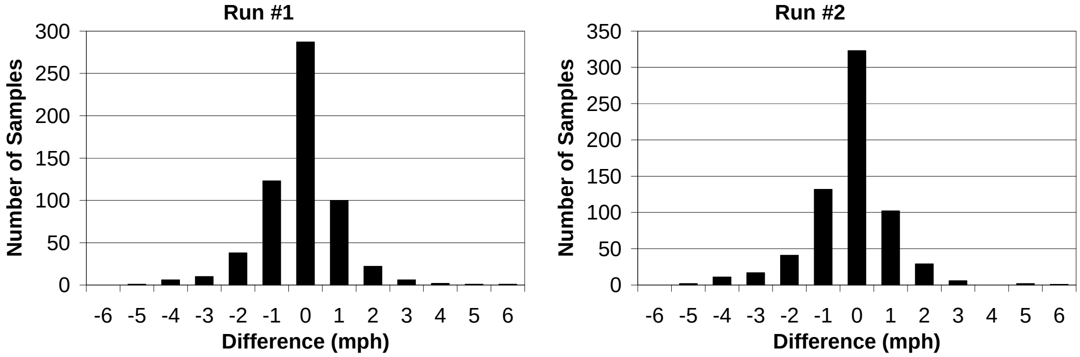

Figure 9-2: Vehicle 2 (1998 Ford Ranger), runs 1 & 2

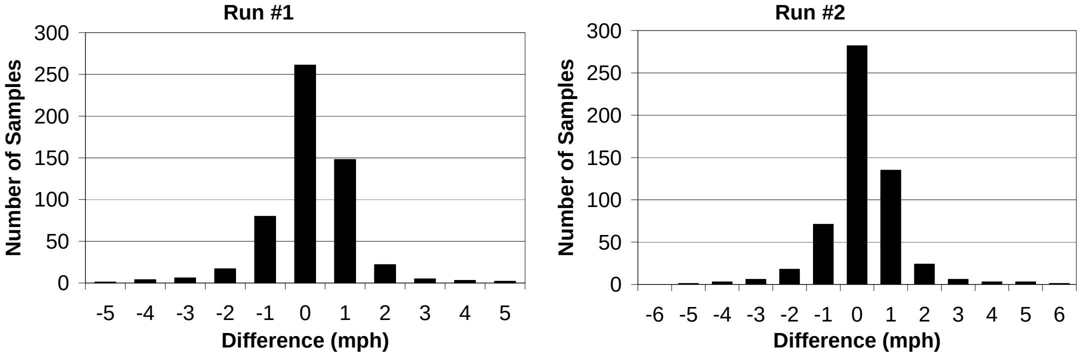

Figure 9-3: Vehicle 3 (1999 Dodge Stratus), runs 1 & 2

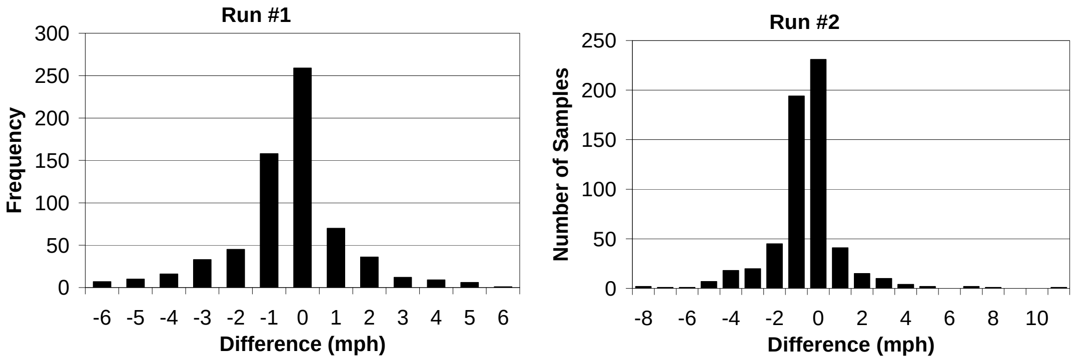

Figure 9-4: Vehicle 4 (2001 Chevrolet Malibu), runs 1 & 2

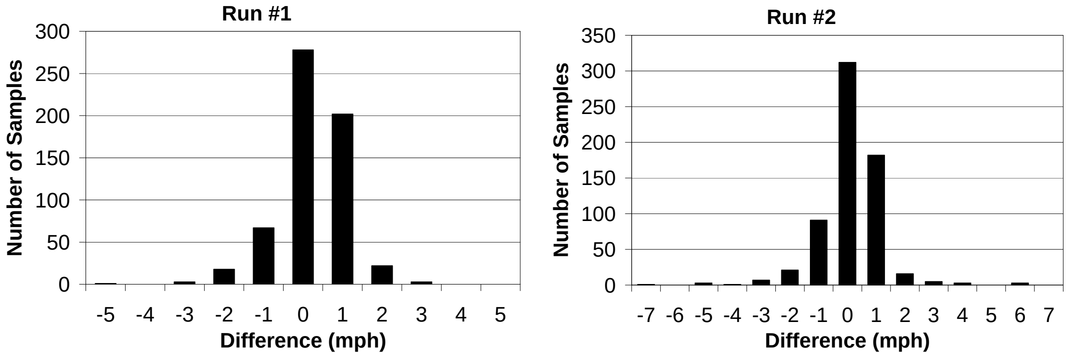

Figure 9-5: Vehicle 5 (1997 Volkswagen Jetta), runs 1 & 2

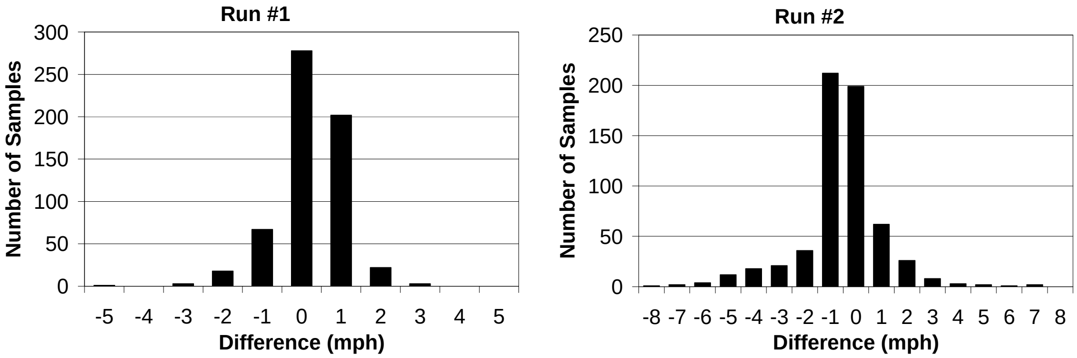

Figure 9-6: Vehicle 6 (2002 Chevrolet Venture), runs 1 & 2

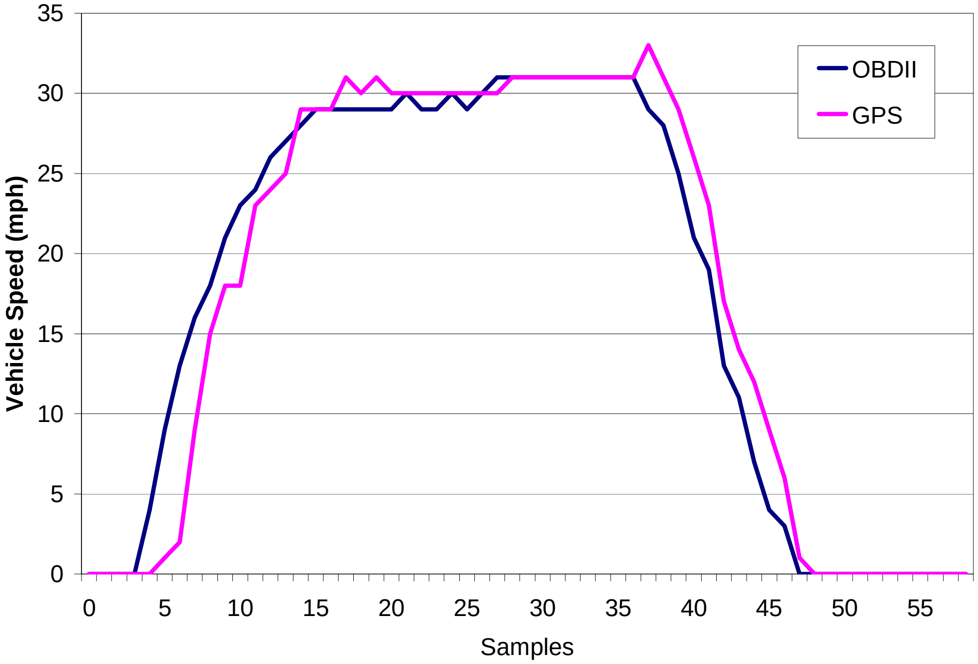

Figure 9-7: Comparison of vehicle speed during acceleration to deceleration event - Vehicle 4, run 2 (2003 Chevrolet Impala)

Figure 9-8: Comparison of vehicle speed during deceleration to acceleration event - Vehicle 6, run 1 (2002 Chevrolet Venture)

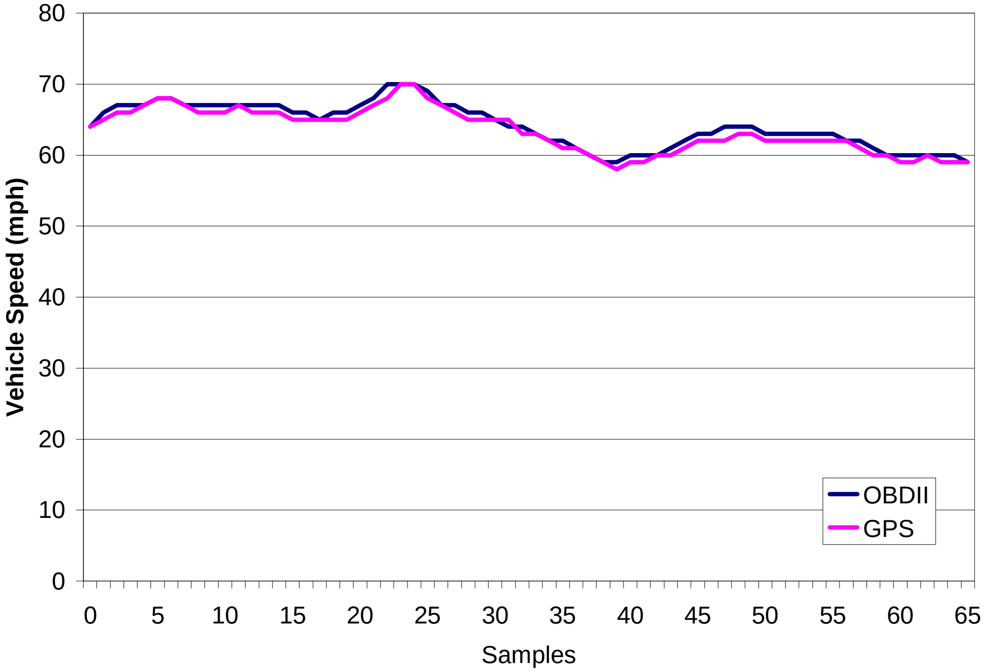

Figure 9-9: Comparison of vehicle speed during steady state event – Vehicle 5, run 2 (1997 Volkswagen Jetta)

9.2 System Observations

Overall, the system was able to perform all the functions as originally intended. Each component, module, and piece of software of the system was successfully demonstrated. A primary goal of this project was the completion of a demonstration unit for use along the demonstration route. Therefore, a qualitative method to evaluate the operation of the TDSS was though actual on-road trial runs.

The computer system, sensors, and software operated within the acceptable limits. The system processed all data and was able to determine the vehicle state once every second. The 1 Hz processing rate was determined sufficient to provide quick system response without requiring a large amount of processing. The processor never reached higher than 30% load, which would suggest that system would be capable of additional processing if needed.

The 1 Hz processing rate allowed the system to provide quick warning responses to the driver in the event of a detected infraction. However, in some cases the warning message was delayed if there were multiple infractions occurring simultaneously. Since the warning messages lasted up to 5 seconds, the feedback system would have to wait until the first message had been delivered before providing a warning for a second infraction. If the second infraction occurred and ended while the first message was being given, no message would be given. If the second infraction continued, the second message would be given once the first message ended. The longest it would take for a message to be delivered to the driver would be 5 seconds multiplied by the number of additional infractions. For example, if three infractions were occurring simultaneously, it might take 10 seconds before the start of the final message is delivered. Since the current system uses auditory voice commands, the commands could not be delivered simultaneously because the messages would have become confusing. If the system were to include additional feedback mechanisms (such as haptic or visual), simultaneous warnings could be used more appropriately. This implies that more human factors expertise should be considered in how to deal with multiple warnings or feedback. Through human factors testing, we can determine the effectiveness simultaneous warnings or delayed warnings, and decide which method is most appropriate.

The speed feedback component of the TDSS performed well during demonstrations, but some errors were detected during trial runs. In most cases, the speed limit feedback component was able to recognized speed limit changes that corresponded to actual speed limit changes in the real world. Since the speed limits were defined internally to the system through the Hennepin County and Mn/DOT speed limit databases, the accuracy of the system relies on the accuracy of the database. In some cases, the speed limits in the database did not always match the real world limits. There were likely several reasons that the system did not correctly identify the real world speed limit. The primary reason is that the speed limit database is not entirely correct. The speed limit database may be out of date, and may not be updated as frequently as needed. Therefore, changes to speed limits that occurred in the real world may not have been updated within the database. Or, the speed limit was entered incorrectly, or the location of the speed limit zone is not accurately or correctly entered. Finally, it was observed that in some cases a staggered speed limit zone that existed in the real world was not reflected in the database. In some cases the staggered zone was indicated by no speed limit, but in others there was no indication of the staggered zone; the speed limit zone was simply entered as the start or end of the next zone or halfway in between.

Clearly, the accuracy of the speed limit database is crucial to the operation of the speed limit feedback system. Given the inaccuracies observed, the current state of the database is not acceptable for widespread deployment. The database needs careful attention to reduce the number of inaccuracies in sign location and speed limit. The number of errors in the current database was not quantified since this was not within the scope of this project. However, through observations during trial testing throughout the county, it was discovered that many errors are present in the current database, which may be the result of a lack of updating to reflect real world changes. Thus, a concerted effort to improve the database would need to take place before widespread deployment could be considered.

The curve speed feedback system performed very well. In all cases tested, the curve speed, curve direction, and curve location in the database matched the real world. However, the look-ahead distance did not always correspond to the location of the actual road sign. The placement of the sign on the road is ultimately at the discretion of the traffic engineer, and the advanced sign placement guidelines are only meant to be a minimum distance. It was observed that the road sign was often placed well in advance to the warning distance determined by the TDSS. In these cases, the sign may have been purposefully placed further in advance than the computed location. Differences in the actual sign location and calculated sign location can also be the result of the estimation procedure to calculate the starting location of the curve. Since the digital map data is used to estimate the curve length, the imprecision of the map may result in an error of the curve length calculation. During the demonstrations, the curve warnings were provided at a reasonable distance from the start of the curve. Similar to the speed limit database, the curve speed database needs to also be carefully examined. Although curves along only one stretch of road (CSAH 15) were tested, and the curve information was observed to be accurate, all curve locations should be verified on all other roads.

The real-time text messaging system performed as intended. Since the system was set-up to send a text message to a cell phone located inside the vehicle, the timing between the when the message was sent and when it was received could be observed. In most cases the message was received within approximately 10 seconds. In a few instances, the message delay was sometimes on the order of several minutes between when the message was sent and received. In these situations, the delay was caused by the service provider, and it is not within the control of the system to speed up the response time. In most cases, however, there were no problems.

The fingerprint sensor performed well during the demonstrations. Since the fingerprint sensor uses a small scanner to enroll the fingerprint, the scan surface should be kept clean. On one occasion, the scanner surface had become dirty, and the reader could not identify the fingerprint. Once the surface was cleaned, there were no problems with the fingerprint identification.

The seatbelt monitor was successfully demonstrated, with only a minor issue in the system response timing. It was noticed that the analog acquisition (see Appendix E) board had a slow response to voltage changes. (This may have been the result of an issue between the acquisition board and the motherboard. This issue was not observed when using a Versa Logic motherboard, only on the Ampro board.) The seatbelt switch was either +12V when buckled, or 0V when unbuckled. Due to the slow response of the acquisition board, a voltage threshold of +7.5V was set as a lower limit for buckled status. However, the system could not update the seatbelt status until this threshold had been reached. In some cases, the seatbelt status was not updated through several (one second) cycles. This was only an issue when the driver had fastened their seatbelt and the system subsequently delivered the seatbelt warning. This is an annoyance because the system did not detect the change, but warned the driver even after they had buckled. An incorrect warning never lasted more than one message length.

10. Discussion

10.1 Role of TDSS in Graduated Driver Licensing

A TDSS can expand the options available of future Graduated Driver Licensing (GDL) programs if adopted by local licensing agencies. As of 2006, most US states and the District of Columbia have some type of GDL system in place. Table 4-3 of Chapter 4 shows the type of restrictions common to GDL programs, and the number of states having such restrictions (IIHS, 2006). Current GDL programs are designed to allow teenagers to gradually gain experience by driving during low-risk situations. Restrictions may be placed on high-risk driving situations such as night driving, driving with passengers, or driving without a supervising adult. Other restrictions may be placed on the age at which the driver gains full licensure and the number of hours of behind the wheel experience the driver has logged. Table 4-3 also gives the IIHS recommendation associated with each restriction, which has yet to be fully met by a single state (IIHS, 2004).

The safety benefit of GDL systems has been clearly demonstrated by a reduction in crashes (Hedlund, Shults, & Compton, in press; Hedlund & Compton, 2005; Simpson, 2003; Shope & Molnar, 2003). Additionally, parents in GDL states are better able to establish and place restrictions on teen drivers (Hartos, Simons-Morton, Beck, & Leaf, 2005). However, no GDL program currently requires the use of technology that limits the speed of the driver, ensures seatbelt use and/or monitors alcohol use. As discussed by Ferguson (2003), GDL systems typically attempt to keep teen drivers out of hazardous situations such as night driving, or driving with passengers, rather than dealing with risk factors directly.

A TDSS may allow GDL systems to incorporate new requirements and provides a way of monitoring compliance. There is a need for continuous GDL monitoring and enforcement because GDL will loose its effectiveness if teen drivers don't comply with its restrictions. A survey of police officers in North Carolina showed that they were unfamiliar with specific GDL provisions, and enforcement of GDL was not a high priority (Goodwin & Foss, 2004). To solve the issue of enforcement, a TDSS system could serve as a method to monitor some of the current GDL restrictions (e.g. night time driving restrictions). It could also serve as a supplement to current GDL programs so that additional restrictions can be placed on behavioral risk factors, such as seatbelt nonuse. Williams et al. (2003) and McCartt & Northrup (2004) have suggested the need for GDL to add a seatbelt requirement. With the addition of a TDSS system, one can design a GDL program in which drivers can be automatically graded based on compliance and "graduate" to less restrictive stages of the GDL program. The resulting program encourages compliance through positive reinforcement and could lead to an even more significant decrease in teen driver fatalities.

In addition to enforcing current GDL restrictions, a TDSS could be capable of enforcing recommendations that can potentially become part of GDL if future programs meet the standards set by IIHS shown in Table 4-3. Perhaps a TDSS could include more sophisticated technology designed specifically for use with GDL programs. If this were the case, the TDSS could include components that not only recognize the driver and supervisor, but all passengers, to facilitate enforcement of the passenger restriction. Additionally, the system could include a component to block cell phone use while the vehicle is being operated to enforce cell phone use restrictions. The cost and feasibility of including these and additional technologies may limit which ones will be selected for use in a TDSS. For example, a lane departure warning system should also be considered for inclusion, but such systems are not at present a low cost option, which may preclude many from purchasing a TDSS. As additional technologies improve and become more cost effective, they may become more appropriate for consideration.

GDL tends to focus on the subset of teenagers between the ages of 16 and 18 years old. Therefore, if GDL is used as an avenue to implement a TDSS, the system should be designed specifically for GDL aged drivers. As previously discussed, a goal of the TDSS is to develop safe driving habits immediately after licensure. If safe habits are developed early on, there is potential for these drivers to maintain safe habits even after they have graduated from the GDL program. Therefore, safety among slightly older (19-24 years old) young drivers could likely improve if they had previously used a TDSS.

10.2 Privacy and Liability Concerns

As Bennett and Raab explain in their book *The Governance of Privacy*, the protection of privacy through public policy and technology can be socially important. Therefore, if such systems are included as part of a GDL program, it is important to maintain an appropriate level of privacy for teenage drivers. Teenagers do have an increasing expectation of privacy as they grow older. The tension and conflict that occurs related to the increased expectation of privacy is the teenager's parent's increasing concern about the risky, life threatening behavior that parents observe or fear on the part of their child. This conflict is particularly of concern by parents in the driving arena. Parents can and do appreciate the significant risk of death or injury that can result from negligent, inattentive or aggressive driving. Teenagers on the other hand do not appreciate or are not aware this injury or death dynamic. Consequently, parents' concerns about the traffic related deaths or injuries that their child might experience outweigh a teenager's expectation of privacy. The use of TDSS technology creates an increased conflict in the area of parent/teenager privacy conflict. In order to best protect the privacy and address the privacy concerns about using a monitoring system, some questions need to be answered before the TDSS is incorporated as part of a GDL program. These include: How will the security of the data be protected, especially if it is wirelessly transmitted to a GDL agency? What type of data should be transmitted, and how should it be used? Who should have access to the data? Who does the data ultimately belong to? How long should the data be retained? Should data only be collected with the driver's consent? Should the driver also be allowed access to the data, and make corrections to the data if need be? Should the data be allowed to be used in court, or in a liability claim against the driver? Should the data be accessible by insurance companies? What the potential repercussions if that data is misused? These questions will need careful examination before we proceed with a plan to implement a TDSS as part of a government run GDL program.

Vendors or car makers who install such a system may have liability concerns with regard to an accident that occurs when a teenage driver is operating a vehicle equipped with such systems. The system may fail to operate properly, may not be used properly, or may have other unintended results. A better understanding of how a driver responds to such technology needs careful attention, and any negative consequences of such technology will need to be evaluated.

It should be noted that the liability issue has not prevented car manufactures from installing other dynamic safety equipment such as ABS brakes or traction control devices.

An example of a negative behavioral response would be a teen driver who games the system, i.e. intentionally operates a vehicle equipped with such a system in an unsafe manner in an attempt to determine if they can reach, if not exceed, the safety operating parameters built into the system in order to obtain the warning. The system software could be designed to detect and limit future operation of a teen's vehicle if a pattern of such operation was detected. A factor that could mitigate this intentional unsafe operation dynamic, and which further reinforces the need for a reporting function, is that the reporting function would show the parent (or the GDL supervisory agency) that the teen drove in an unsafe manner.

10.3 Recommendations

To be most effective, a TDSS device should be used as soon as the teen begins driving because it may have the most benefit during this time period. As discussed in section 1.2.4, teen drivers are most likely to be involved in a crash in the time period immediately after licensure. A TDSS device should also provide real-time feedback and reporting. This in-situ approach using real-time feedback gives the driver instantaneous warning to correct their behavior. Through practice, this system could eventually coach the driver to develop safer habits behind the wheel.

The reporting component should also include the capability to evaluate changes in driving behavior between driving episodes. The goal would be to observe driving operational trends which ideally should show a trend towards decreased risk taking. A parent could review the vehicle operation reports, and impose restrictions on the teen's driving until improvement in their driving behavior becomes evident. This type of reporting can serve as a tool to enforce a parent-teen 'driving contract.' It can also serve to provide the information needed to enforce present or future GDL requirements.

The parental role is also a key factor in the success of such a device. A study by Beck, Raleigh, and Shattuck (2001) showed parents are often unaware of the extent to which their teen engages in risky driving, drives too fast, do not wear a seatbelt, and ride with a drinking driver. A TDSS reporting system has the ability to monitor this information and to prompt parents to become actively involved in the training of their teen driver. Low parental monitoring and lenient restrictions are shown to be related to risky driving behavior and motor vehicle crashes (Hartos, Eitel, & Simons-Morton, 2002; Hartos, Eitel, Haynie, & Simons-Morton, 2000; McCartt, Shabanova, & Leaf, 2001). Thus, parental involvement is an integral component to making successful improvements in teen driving behavior. If we hope to make a significant impact in reducing the number of teen fatal crashes, we must also make a concerted effort to get parents more involved in the training of their teen drivers. We also need to ask ourselves what is a reasonable amount of information, and how often should the information be reviewed by the parents so as not to overload them, which could discourage them from being involved. Thus, an evaluation should take place of how TDSS can best process and present the information so that parents and teens can best benefit from it.

In addition to being used by teen drivers and their parents, a TDSS can also be used by the insurance industry. If shown to be successful, the system could eventually lead to insurance premium reductions among those drivers using the device. Progressive Auto Insurance (2004) is currently conducting a pilot study using a driver-monitoring device called TripSensor™ (patent pending). The device has been offered to 5000 drivers in Minnesota, and it tracks how much, when, and how fast they drive. Drivers with the device can receive up to a 25% discount through low-risk driving. A similar device is also being tested in a pilot study by Norwich Union (2004), the largest insurance company in the UK. The Pay As You Drive^{TM} device is licensed under Progressive's patent application and tracks how much, when, and where a vehicle is driven.

Unfortunately, these devices do not go beyond providing a recording function. Providing feedback and forcing functions should be considered in order to achieve significant teen road fatality reductions. Therefore, a TDSS device could be used as part of insurance discount programs, while *also* providing additional safety benefits.

As a result of this project and the lessons learned through the development of the TDSS, recommendations can be made about how to improve the TDSS design and how to move forward into future phases of this project. The TDSS described in this document was designed for demonstration purposes, but considerations for future iterations of the TDSS were considered. Packaging considerations of the system have led to the conclusion that a Personal Digital Assistant (PDA) or smartphone-based system should be developed for future demonstration. Several features of the TDSS could piggyback on current location based services for example used on cell phones. The ISA components and reporting component of the TDSS would be possible using a GPS-enabled cell phone. However, considerations will need to be made on how the system will monitor seatbelt use, alcohol use, and carry out driver identification. As discussed in Chapter 11, some features of a TDSS may be best developed and integrated into a vehicle by the automotive manufacturer.

As explained in Chapters 6 and 7, the TDSS is currently limited by the availability of data used in the ISA system. For a TDSS to be successful there needs to be a concentrated effort to increase the accuracy and availability of speed limit data, curve speed data, and weather data. Due to the current lack of availability of speed limit data, cooperation much be achieved on all jurisdictional levels (state, county, and city). As previously discussed, each traffic authority is responsible for assigning speed limits to roads under their jurisdiction, and some do not keep an organized record of speed limits and sign locations. Thus, a standard for logging speed limit data should be created, which at the least should include the road's TIS code, posted limit, and location of the signs or speed zones.

Perhaps the first step to making the curve speed data available is the collection and digitization of the data. Curve speed data comes from curve study sheets prepared by traffic engineers and the information included in the curve study sheets is given in Table 6-2. County traffic engineers are responsible for assigning the advisory curve speeds in their respective county. There is a standard guideline used for determining curve speeds and logging the information, which is given in Section 6-6.06 of Minnesota's Traffic Engineering Manual (Mn/DOT, 2004). A single database should be created by collecting the curve speed study sheets from all counties and digitizing the data by entering it into a database. Having a digital collection of the data will not only make updating the database easier, but it will perhaps make this data more accessible for other projects that could rely on this information. To increase the positional accuracy of the calculated warning location in the curve speed component, the length of the curve should be an included measure given in the curve study sheets. So, when the traffic engineers log the position of the curve, they should also log the starting and ending position.

In order to make the RWIS weather data useable to the TDSS, some improvements need to be made. Currently, there are only two RWIS sensors in Hennepin County. That means that the system must rely on the information from a small number of sensors to represent a large geographic area. In some situations, the closest sensor may be several miles away, and therefore, the weather and pavement conditions at that sensor may not reflect the conditions at the vehicle's location. To improve the system, additional sensors should be added to the RWIS network. The exact number of sensors and their locations will require further investigation. Additionally, the data from the current sensors is often times outdated, and it is not updated as frequently as the system indicates. Weather data on the RWIS server is updated every 10 minutes, but often times the Hennepin County data is not current, meaning that the data in some cases is several hours or days old. The system needs to be more reliable and up to date if the RWIS is to be used as a reliable source of real-time weather information.

If weather data becomes more reliable, it's possible that the TDSS could even make use of forcing functions to prevent driving during severe inclement weather. Since beginning teen drivers may lack the skill and experience necessary to drive in high risk situations, such as during adverse weather, an interlock feature could be used preclude driving during such conditions. The weather-based speed practices of the DOTs described in Chapter 7 are designed for the average motorist, not a teenage driver specifically. Acceptable limits on weather conditions and the corresponding safe travel speeds for teenagers should be considered separately, and could be used as a basis for a weather-based interlock. Another forcing feature of the TDSS could prevent a teen driver from using the vehicle's cruise control, which would require that the driver maintains a higher level of attention to safe travel speeds and speed limits.

The speed limit and curve speed components are an example of in-vehicle road signing. The need for accurate sign information for the speed components of the TDSS raises a question about what other road sign or other Traffic Control Device (TCD) information could be included. An effort to make all TCD location information available to in-vehicle systems, such as the TDSS, should be made. If TCD locations and sign details were included in a database, this information has great potential for safety benefits to in-vehicle systems. For example, a database that includes the location of the stop sign (and stop bar) could for example be used to driver if they are distracted and don't decelerate appropriately. Using ITS technology, built around in-vehicle computing systems, road signing could go well beyond providing the traditional road side warnings to the driver, it would also be able to ensure that the driver is aware of both current conditions as well as those that lie ahead.

Seatbelt interlocks may be best introduced by automobile manufacturers because all vehicles currently manufactured contain much of the necessary technology. All vehicles contain belt fastening sensing technology for the driver. Vehicles also have an interlock associated with the transmission, which prevents the vehicle from being started if the transmission is in a driving gear. It would be trivial for manufacturers to combine these features to implement a seatbelt interlock that could be designed to facilitate seatbelt use among teenagers. However, manufacturers do not currently make a seatbelt ignition interlock an option.

11. Conclusion

As a result of this project, a Teen Driver Support System (TDSS) was developed through a combination of in-vehicle technology to monitor and correct unsafe teen driver behavior. The technologies were selected and developed with the specific intent to address the common risk behaviors that play a role in a majority of teen driver fatalities. The TDSS uses a combination of in-vehicle technologies using forcing, feedback, and reporting functions. Specific behaviors that were targeted include speeding (above the posted limit or too fast for conditions), seatbelt use, and alcohol use. The TDSS also takes advantage of reporting technology so that certain components of the GDL programs can be enforced, and the benefits of GDL can be maximized. In this way, the TDSS is able to improve already existing GDL programs that deal with young drivers' lack of experience, which also contributes to their propensity to crash. The information generated by the TDSS log report can also be used by a GDL monitoring agency as "report card," which could serve as the basis for graduating drivers to less restrictive phases of GDL. The reporting component also provides parents of the teen driver a method to monitor driving behavior, so that the parent can become actively involved in the training of the teenager. The resulting TDSS described in this document could significantly decrease the number of teen crash fatalities.

The TDSS represents the first implementation of a system in which all of these technologies have been combined into a single system with a single focus on teen drivers. The TDSS takes into account the limitations of existing teen driver systems by including dynamic context based speed warnings, forcing functions for seatbelt use, and an optional forcing function for alcohol. The TDSS speed limit component differs from other ISA systems that only provide speed limit information in that the TDSS also includes safe travel speeds based on road geometry and weather conditions. In comparison to the curve warning systems that have been developed for other research projects (EDMap, UMTRI), the TDSS curve warning system was designed specifically to function without the need for a high accuracy digital map. Other systems rely on the use of the map to determine an appropriate speed based on road curvature, while the TDSS takes advantage of existing data that precisely defines the location of advisory curve speeds. The TDSS uses an existing weather data network infrastructure and cellular network infrastructure to collect real time weather information for determining safe travel speeds. Since beginning drivers may not be aware of the risk, or lack the experience to safely drive in such conditions, the TDSS provides speed guidelines for a beginning driver. The TDSS is also the first in-vehicle system that has been designed with the capability of enforcing certain GDL restrictions. Since GDL lacks a proper method of enforcement, the reporting component of the TDSS has the potential for use in GDL programs so that drivers can be graded on their behavior, and thus can serve as a basis for graduating to less restrictive phases of GDL. The TDSS also provides an opportunity for enforcement of the other GDL provisions that are not currently included in the program, such as seatbelt use.

To maximize the benefit of a TDSS system, human factors research should be conducted to optimize the form of feedback given to the teen driver and the reporting format provided to parents (or other authorities). To support these human factors objectives, additional research is necessary to identify thresholds for risk behavior and metrics to quantify driving performance.

Whereas this projects that a TDSS is technically feasible, there remains the need to provide the human factors data to support an effective and acceptable design.

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Appendix A.

Summary of Several Teen Driving Aids

Product	**RS-1000**	**CarChip E/X**	**DriveRight 600**	**SignalTrac**	**NetworkCar**	**SmartDriver**	**DriveCam**	**TeenArriveAlive**
Manufacturer	RoadSafety	Davis Instruments		SignalTrac	NetworkCar	SmartDriver	DriveCam	TeenArriveAlive
website	roadsafety.com	davisnet.com		signaltrac.com	networkcar.com	smart-driver.com	drivecam.com	teenarrivealive.com
base price ($)	280	179	395	499	995	495	1,200	N
activation fee ($)	N	N	N	145	90	69	N	50
service fee ($)	N	N	N	399/yr	108/yr	100/yr	N	240/yr
Data Collected								
video	N	N	N	N	N	N	R	N
location (GPS)	R**	N	R	R	R	N	N	R
speed	FE	R	FE	R	N	R	N	R
distance	R	R	R	R	N	R	N	R
acceleration	FE	R	FE	N	N	N	R	N
deceleration/braking	FE	R	FE	N	N	N	R	N
lateral acceleration	FE	N	N	N	N	N	R	N
throttle position	R	R	N	N	N	R	N	N
time of day	R	R	R	R	R	R	N	R
driver seatbelt use	FE*	N	R*	R*	N	N	R	N
alcohol	N	N	N	N	N	N	N	N
unsafe backing	FE*	N	N	N	N	N	N	N
Notification								
real-time GPS	R**	N	N	R	R	N	N	R
in-vehicle display	N	N	FE	N	N	N	N	N
online reports	N	N	N	R	R	N	N	N
e-mail alerts	N	N	N	R	N	N	N	N
cellphone alerts	N	N	N	N	N	N	N	R
Additional Features	1,3		2,3	1	1			1

*feature is optional	
**feature is not yet available	
(1) broadcasts via cellular connection	
(2) LCD display on dashboard	
(3) auditory feedback	

FUNCTIONS
FO - FORCING
FE - FEEDBACK
R - REPORTING
N - NOT AVAILABLE

Figure A-1: Chart summarizing several commercially available teen driving aids based on their features and functions

Table A-1: Descriptive summary of several teen driving aids

Product	**Integration**	**Data**	**Functions**	**Limitations**
RoadSafety RS-1000	Connects to vehicle's diagnostic port; optional connections to monitor seatbelt use	Speed, distance, acceleration, hard braking, throttle use, hard cornering, time of day, seatbelt use.	**Reporting:** Data collected for off-line viewing on home computer. **Feedback:** Real-time auditory alarm based on data thresholds.	Reporting and feedback function thresholds are user defined and static; no location data collected.
Davis Instruments CarChip E/X Alarm	Connects to vehicle's diagnostic port.	Speed, distance, acceleration, braking, throttle use, time of day.	**Reporting:** Data collected for off-line viewing on home computer. **Feedback:** Real-time auditory alarm based on data thresholds.	Collects a limited amount of information; no location data collected; feedback and reporting functions are user defined and static.
Davis Instruments DriveRight 600	Connects to vehicle's diagnostic port; optional connections for seatbelt or brake use; includes LCD dash mounted display.	Location, speed, distance, acceleration, braking, time of day, seatbelt use.	**Reporting:** Data and location collected for off-line viewing on home computer. **Feedback:** Real-time auditory alarm; in-vehicle display of data.	Does not provide real-time reports for viewing by parent and/or other authority.
SignalTrac	Mounts beneath the vehicle's dashboard; connects to GPS and cellular antennae; optional connections for seatbelt use and passenger door use.	Location, speed, distance, time of day, seatbelt use, passenger door use.	**Reporting:** Real-time e-mail alerts to parents triggered by location and speed of vehicle; online vehicle location and speed tracking and data reports.	Lacks real-time feedback feature; does not provide context for speeding; expensive.
NetworkCar	Permanently installed in vehicle.	Location, time of day.	**Reporting:** Online vehicle location tracking.	Only provides location information; no feedback function.
SmartDriver	Connects to vehicle's diagnostic port.	Speed, distance, throttle use,	**Reporting:** Generates report of collected data	Only provides limited information; thresholds are user

		engine RPM, time of day.	and for off-line viewing on home computer	defined and static; location data not collected.
DriveCam	Mounts to rearview mirror.	Interior and exterior video, interior audio.	**Reporting:** Records video and audio for off-line viewing by parent; triggered by onboard accelerometer. **Feedback:** Small LED light indicates recording.	Requires review of video footage; sensitive to false positives; does not directly monitor seatbelt use; no adequate feedback.
Teen Arrive Alive	Integrated with cellular phone.	Location, speed, distance, time of day.	**Reporting:** Online and dial-in vehicle location tracking.	Requires use of cell phone; easily disabled; limited features.

Appendix B.

Summary of proposed features of TDSS

Table B-1: Descriptive summary of TDSS features

Feature	Summary	Benefit	Implementation
Intelligent Speed Adaptation (ISA)	Speed limiting technology; provides driver with feedback warnings based on local speed limits; includes dynamic speed warnings based on road curvature, weather conditions.	May address crashes caused by speeding and driving too fast for conditions.	Requires onboard processor and combination of positioning sensor/digital map/speed limit database; wireless access to road weather data through cellular connection.
Seatbelt Interlock	Requires driver to fasten their seatbelt; technology prevents full vehicle functionality until seatbelt is engaged.	May address fatalities attributed to lack of seatbelt use.	Using existing seatbelt wiring it is possible to implement an aftermarket interlock; car manufacturers also have an opportunity to include this feature as an OEM option.
Alcohol Interlock	Requires driver sobriety prior to vehicle operation; technology prevents driver from starting vehicle until a breath alcohol test has been passed.	May address crashes caused by driver impairment due to alcohol use.	There are currently several manufacturers of interlock systems; they are generally permanently installed in vehicle; could be optional stand-alone feature.
Data Logger (Off-line and Real-time)	Provides parent with record of teen driving performance; allows parents to receive notification of unsafe behavior via text messaging, email, or internet.	Enables enforcement of GDL provisions; gives parents and/or other authorities a basis for evaluating and correcting driving behaviors; removing anonymity may reduce likelihood of unsafe driving behavior.	Using onboard processor, performance data can be collected and transferred for off-line viewing; using wireless cellular device, real-time reports can be sent.
Driver Interface	Provides driver with real-time feedback based on unsafe driving behavior or potential hazards.	Feedback may condition driver to conform to safe driving behavior; may prevent unsafe behavior before it occurs.	Possibilities include auditory, visual, and/or haptic feedback modalities; modality should be based on driver evaluations of acceptance and success.
Driver Identification	Identifies driver and supervising adult	Enables monitoring of GDL provisions on	Current biometric fingerprint technology can

	(such as parent) in the vehicle; requires prior enrollment of fingerprints.	nighttime driving, number of training hours, mandatory holding periods; allows parent to disable system; allows multiple configuration.	be incorporated as a low cost method of occupant identification.

Appendix C.

RWIS Site Sensor Information

Table C-1: RWIS atmospheric data

Data Field	Units
System Id	Integer
Site Id	Integer
Date/Time	mm/dd/yy hh:mm:ss am/pm (12 hr. GMT)
Air Temp	Degree C.
Dew Temp	Degree C.
RH	Percent
Wind Speed Avg	Km/hr.
Wind Spd Gust	Km/hr.
Wind Direction Avg	Azimuth – degrees
Wind Direction Max	Azimuth – degrees
Precip Intensity	Text
Precip Type	Text
Visibility	Meters
Air Pressure	Millibar
Precip Rate	Cm/hr.
Precip Accum	Cm over 24 hr starting at Midnight local time
10 min Solar	Joules per square meter
24 hr Solar	Joules per square meter
24 hr sun	Minutes over 24 hours
Air Temp Max	Degree C.
Air Temp Min	Degree C.
Wet Bulb Temp	Degree C.
Last Precip Start	Mm/dd/yy hh:mm:ss am/pm (12 hr. GMT)
Last Precip End	Mm/dd/yy hh:mm:ss am/pm (12 hr. GMT)
1 hr Precip Accum	Centimeters
3 hr Precip Accum	Centimeters
6 hr Precip Accum	Centimeters
12 hr Precip Accum	Centimeters
24 hr Precip Accum	Centimeters

Table C-2: RWIS subsurface data

Data Field	Units
System Id	Integer
Site Id	Integer
SubSensor Id	Integer
Surface Sensor Id	Integer
Date/Time	Mm/dd/yy hh:mm:ss am/pm (12 hr. GMT)
Subsurface Temp	Degree C.
Subsurface Moisture	Percent
Delta-t	Picoseconds

Table C-3: RWIS surface data

Data Field	Units
System Id	Integer
Site Id	Integer
Sensor Id	Integer
Date/Time	Mm/dd/yy hh:mm:ss am/pm (12 hr. GMT)
Surface Condition	Text
Surface Temp	Degree C.
Freeze Temp	Degree C.
Chemical Pct	Percent
Depth	Millimeters
Ice Pct	Percent
Salinity	Parts/100,000
Conductivity	Mhos

Table C-4: Minnesota metro region RWIS sensor information

SITE ID	SYSTEM	HIGHWAY	MILE POINT	DISTANCE FROM CITY/JCT	VIDEO CAMERA	TEMPATURE/HUMIDITY	WIND	BAROMETRIC PRESSURE	PRECIPITATION TYPE/RATE	PRECIPITATION: YES/NO	VISIBILITY	SUBSOIL TEMPERATURE	SOLAR RADIATION
4	330	I-35	157.1	4.5 mi N of Harris		X	X	X	X		X		
75	330	TH169	86.38	2.1 mi N of Jct. 19		X	X	X	X		X	X	
85	330	I - 494	17.65	Jct Hennepin CR 5		X	X			X			
86	330	I -35 W	4.26	Over Minnesota River in Burnsville		X	X			X			
87	330	I - 94	216.63	Junct. 494 Maple Grove		X	X			X			
88	330	I - 694	45.819	Junct. 35E, Little Canada		X	X			X			
89	330	I -35 E	108.5	Cayuga St. Bridge in St. Paul		X	X			X			
90	330	TH 110	4.52	I - 494		X	X			X			

Appendix D.

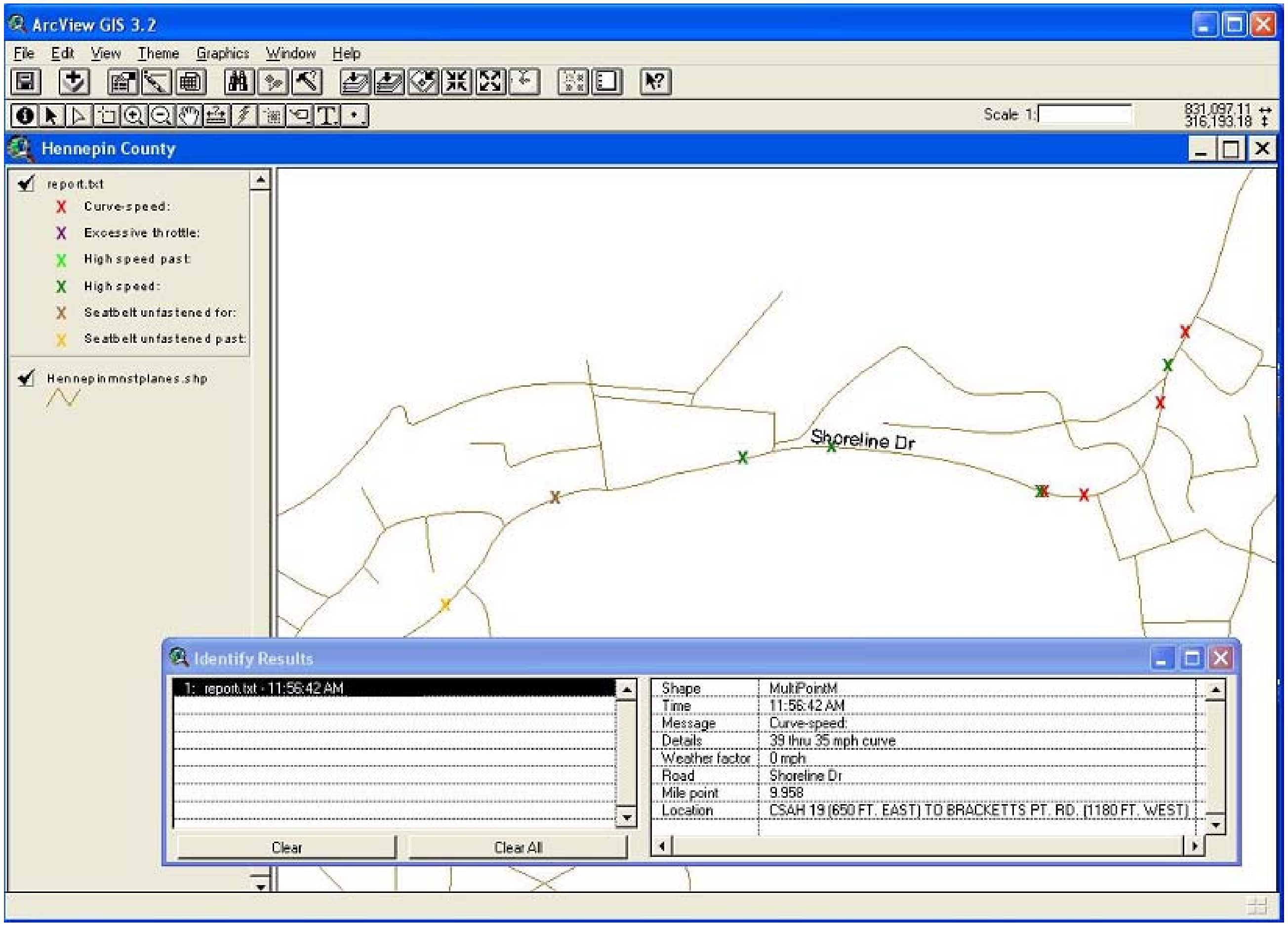
Example TDSS Report

Table D-1: TDSS example report log

Date: Fri Feb 24 2006
Start Time: 11:25:39 AM
Driver Name: Driver
Supervisor Name: Parent

TIME	MESSAGE	DETAILS	WEATHER FACTOR	ROAD	MILE POINT	LOCATION
11:26:20 AM	Seatbelt unfastened for:	0 min 21 sec		N/A	0.949	N/A
11:29:52 AM	Excessive throttle:	62.0/100		I-94	234.137	BEG 6 LN I 394 TO HENN/RAM CL (236.319)
11:30:40 AM	High speed:	63 in a 55	0 mph	I-94	233.332	BEG 6 LN I 394 TO HENN/RAM CL (236.319)
11:32:26 AM	High speed:	57 in a 55	0 mph	I-394	8.515	I 494 TO BEG SL 40 I 94
11:34:07 AM	High speed past:	1 min 0 sec		I-394	6.771	I 494 TO BEG SL 40 I 94
11:34:48 AM	High speed:	64 in a 55	0 mph	I-394	6.05	I 494 TO BEG SL 40 I 94
11:36:05 AM	High speed:	57 in a 55	0 mph	I-394	4.654	I 494 TO BEG SL 40 I 94
11:40:22 AM	High speed:	57 in a 55	0 mph	I-394	0.819	I 494 TO BEG SL 40 I 94
11:40:53 AM	High speed:	57 in a 55	0 mph	I-394	0.24	I 494 TO BEG SL 40 I 94
11:41:16 AM	High speed:	60 in a 55	0 mph	US Hwy 12	157.087	BEG SL 65 CSAH 42 TO SL 55 .2 MI W I-494
11:46:02 AM	High speed:	52 in a 50	0 mph	Shoreline Dr	12.977	ORONO / WAYZATA CITY LIMITS TO RAMP TO LAKE ST. (OLD CSAH 15)
11:47:11 AM	High speed:	43 in a 35	0 mph	Shoreline Dr	11.953	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
11:47:22 AM	Curve-speed:	38 thru 30 mph curve	0 mph	Shoreline Dr	11.953	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
11:47:39 AM	High speed:	37 in a 35	0 mph	Shoreline Dr	11.656	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
11:48:12 AM	Curve-speed:	26 thru 20 mph curve	0 mph	Shoreline Dr	11.473	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
11:48:29 AM	High speed:	38 in a 35	0 mph	Shoreline Dr	11.234	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:49:38 AM	Curve-speed:	38 thru 35 mph curve	0 mph	Shoreline Dr	10.545	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:50:44 AM	Curve-speed:	37 thru 35 mph curve	0 mph	Shoreline Dr	9.861	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:51:08 AM	Curve-speed:	33 thru 30 mph curve	0 mph	Shoreline Dr	9.6	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:51:45 AM	High speed:	42 in a 40	0 mph	Shoreline Dr	9.14	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:52:48 AM	High speed:	42 in a 40	0 mph	Shoreline Dr	8.457	BELMONT LANE (150 FT. EAST) TO CSAH 19 (650 FT. EAST)
11:54:56 AM	Seatbelt unfastened past:	0 min 40 sec		Shoreline Dr	8.651	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:54:56 AM	High speed:	42 in a 40	0 mph	Shoreline Dr	8.881	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)

11:55:07 AM	Seatbelt unfastened for:	0 min 53 sec		Shoreline Dr	8.881	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:56:09 AM	High speed:	44 in a 40	0 mph	Shoreline Dr	9.595	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:56:16 AM	Curve-speed:	39 thru 30 mph curve	0 mph	Shoreline Dr	9.661	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:56:31 AM	High speed:	42 in a 40	0 mph	Shoreline Dr	9.917	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:56:42 AM	Curve-speed:	39 thru 35 mph curve	0 mph	Shoreline Dr	9.958	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:57:12 AM	High speed:	42 in a 40	0 mph	Shoreline Dr	10.365	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:57:23 AM	Curve-speed:	39 thru 35 mph curve	0 mph	Shoreline Dr	10.424	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
11:58:57 AM	High speed:	42 in a 40	0 mph	Shoreline Dr	11.536	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
11:59:25 AM	High speed:	37 in a 35	0 mph	Shoreline Dr	11.835	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
11:59:35 AM	Curve-speed:	27 thru 20 mph curve	0 mph	Shoreline Dr	11.835	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
12:00:21 PM	Curve-speed:	34 thru 30 mph curve	0 mph	Shoreline Dr	12.212	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
12:00:27 PM	High speed:	41 in a 35	0 mph	Shoreline Dr	12.363	ORONO ORCHARD RD. (480 FT. EAST FOR EB TRAFFIC) TO ORONO ORCHARD RD.
12:01:36 PM	High speed:	54 in a 50	0 mph	County Hwy 15	13.236	ORONO / WAYZATA CITY LIMITS TO RAMP TO LAKE ST. (OLD CSAH 15)
12:02:16 PM	High speed:	52 in a 50	0 mph	US Hwy 12	153.497	BEG SL 65 CSAH 42 TO SL 55 .2 MI W I-494
12:06:45 PM	High speed:	63 in a 55	0 mph	I-394	0.871	I 494 TO BEG SL 40 I 94
12:08:20 PM	High speed past:	1 min 0 sec		I-394	2.417	I 494 TO BEG SL 40 I 94



Shape	MultiPointM
Time	11:56:42 AM
Message	Curve-speed:
Details	39 thru 35 mph curve
Weather factor	0 mph
Road	Shoreline Dr
Mile point	9.958
Location	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)

Figure D-1: Example report map (created using ArcView)

Appendix E.

TDSS Computer Specifications

Motherboard:

- AMPRO Littleboard 700
- 933 MHz Low Voltage Pentium III
- 256 MB RAM
- (4) RS-232 Serial Ports
- PS/2 Keyboard and Mouse, AC97 Sound ports
- Dual 10/100BaseT Ethernet interface
- AGP 4X video interfaces
- PC/104-Plus Interface

PC-104 Stack:

- AMRPO I/O Interface Board
- Tri-M Engineering (IDE-104-V2) PC/104 Hard drive adaptor
- VersaLogic (VCM-DAS-1/2) Analog & Digital I/O Module for PC/104

Data Storage:

- IBM Travelstar 4200 RPM 10 GB Hard drive

Enclosure:

- Parvus extruded aluminum enclosure (14” x 6.5” x 6.5”)

Power Supply:

- IPC America (ACE-865V) 12VDC to +12VDC/+5VDC

Appendix F.

Speed Limit Maps

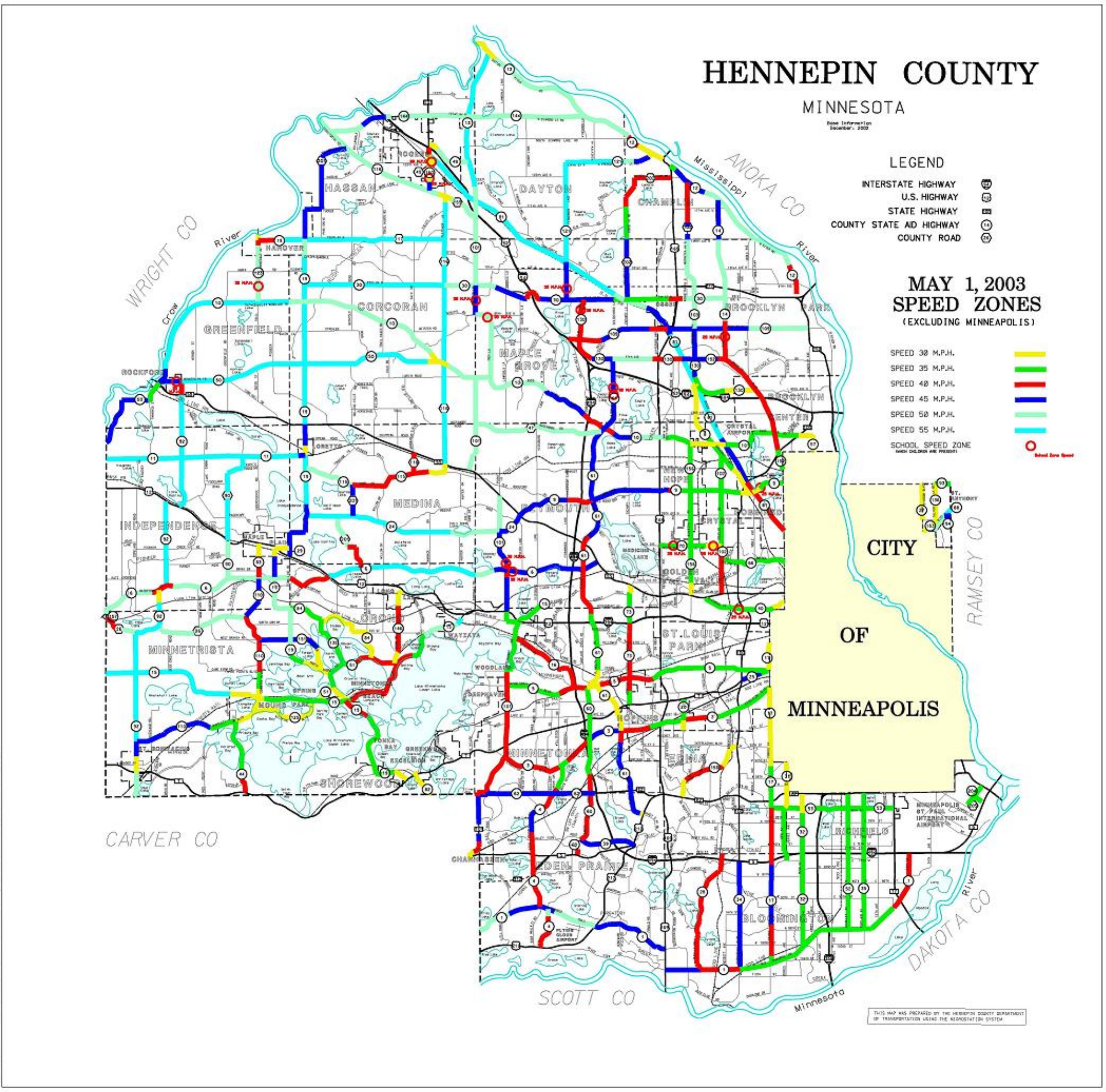


Figure F-1: Speed limits for roads maintained by Hennepin County

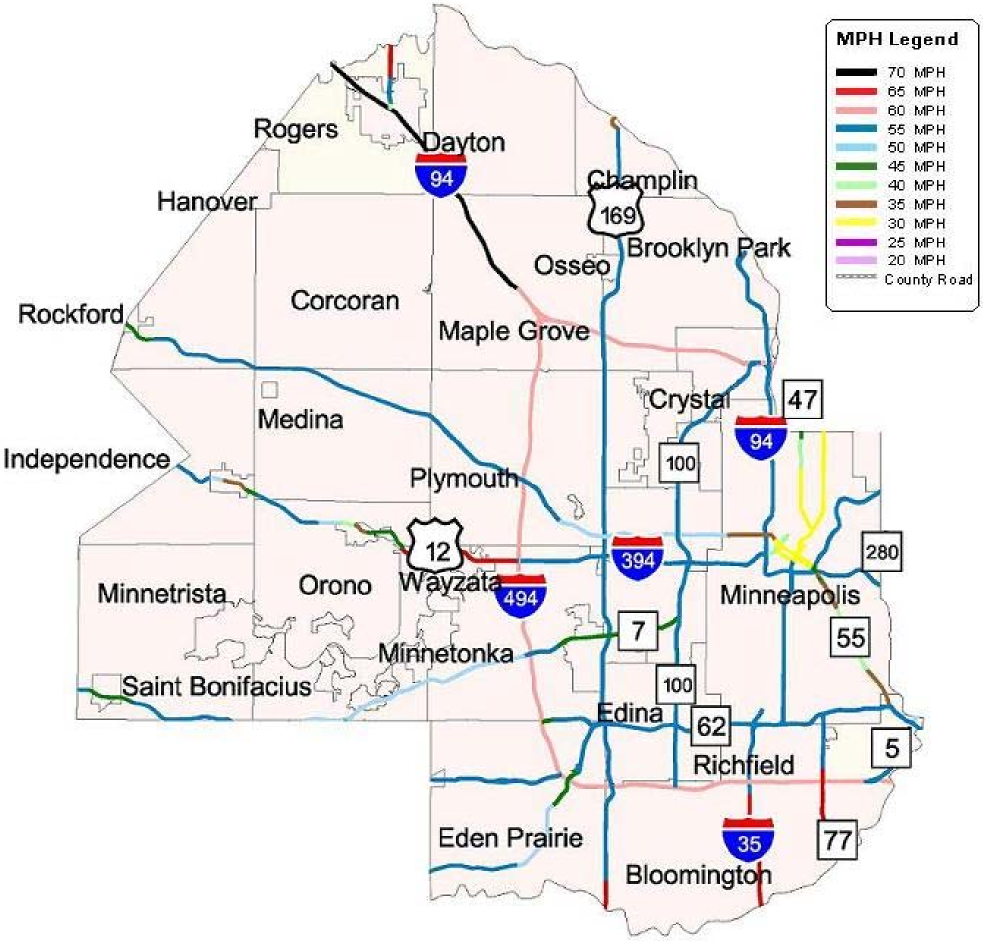
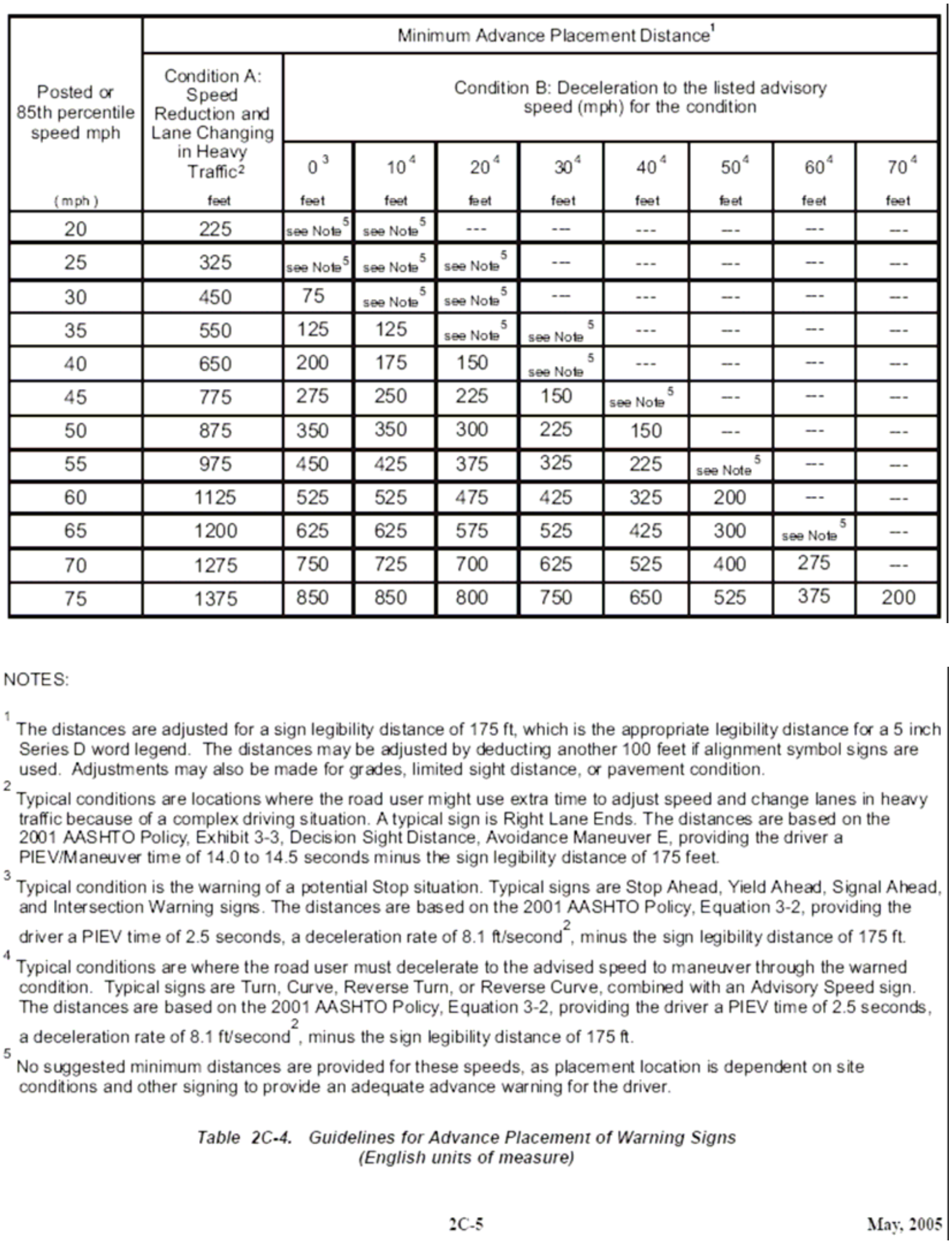


Figure F-2: Speed limits for roads maintained by Mn/DOT in Hennepin County

Appendix G.

Advanced Warning Distance



Posted or 85th percentile speed mph	Minimum Advance Placement Distance[1]								
	Condition A: Speed Reduction and Lane Changing in Heavy Traffic[2]	Condition B: Deceleration to the listed advisory speed (mph) for the condition							
		0[3]	10[4]	20[4]	30[4]	40[4]	50[4]	60[4]	70[4]
(mph)	feet	feet	feet	feet	feet	feet	feet	feet	feet
20	225	see Note[5]	see Note[5]	---	---	---	---	---	---
25	325	see Note[5]	see Note[5]	see Note[5]	---	---	---	---	---
30	450	75	see Note[5]	see Note[5]	---	---	---	---	---
35	550	125	125	see Note[5]	see Note[5]	---	---	---	---
40	650	200	175	150	see Note[5]	---	---	---	---
45	775	275	250	225	150	see Note[5]	---	---	---
50	875	350	350	300	225	150	---	---	---
55	975	450	425	375	325	225	see Note[5]	---	---
60	1125	525	525	475	425	325	200	---	---
65	1200	625	625	575	525	425	300	see Note[5]	---
70	1275	750	725	700	625	525	400	275	---
75	1375	850	850	800	750	650	525	375	200

NOTES:

[1] The distances are adjusted for a sign legibility distance of 175 ft, which is the appropriate legibility distance for a 5 inch Series D word legend. The distances may be adjusted by deducting another 100 feet if alignment symbol signs are used. Adjustments may also be made for grades, limited sight distance, or pavement condition.

[2] Typical conditions are locations where the road user might use extra time to adjust speed and change lanes in heavy traffic because of a complex driving situation. A typical sign is Right Lane Ends. The distances are based on the 2001 AASHTO Policy, Exhibit 3-3, Decision Sight Distance, Avoidance Maneuver E, providing the driver a PIEV/Maneuver time of 14.0 to 14.5 seconds minus the sign legibility distance of 175 feet.

[3] Typical condition is the warning of a potential Stop situation. Typical signs are Stop Ahead, Yield Ahead, Signal Ahead, and Intersection Warning signs. The distances are based on the 2001 AASHTO Policy, Equation 3-2, providing the driver a PIEV time of 2.5 seconds, a deceleration rate of 8.1 ft/second^2, minus the sign legibility distance of 175 ft.

[4] Typical conditions are where the road user must decelerate to the advised speed to maneuver through the warned condition. Typical signs are Turn, Curve, Reverse Turn, or Reverse Curve, combined with an Advisory Speed sign. The distances are based on the 2001 AASHTO Policy, Equation 3-2, providing the driver a PIEV time of 2.5 seconds, a deceleration rate of 8.1 ft/second^2, minus the sign legibility distance of 175 ft.

[5] No suggested minimum distances are provided for these speeds, as placement location is dependent on site conditions and other signing to provide an adequate advance warning for the driver.

Table 2C-4. Guidelines for Advance Placement of Warning Signs
(English units of measure)

2C-5 May, 2005

Source: 2005 Mn/DOT Manual on Uniform Traffic Control Devices

Appendix H.

Test Route: Curve and Speed Zone Information

Table H-1: Curves along CSAH 15 (0427000015) included in the test route

TIS_CODE	ID	DIST	LIMIT	CURVE	INCR	DECR	DESCRIPTION
0427000015	9	9.67	40	30	R	L	At Lafayette Rd
0427000015	10	9.92	40	35	L	R	At Arcola Ln
0427000015	11	9.99	40	40	R	L	At Beach Ln
0427000015	12	10.23	40	35	L	R	550' E. of Ctr of Arcold Brg
0427000015	13	10.4	40	35	R	L	1425' E. of Ctr of Arcold Brg
0427000015	14	10.6	40	35	L	R	2500' E. of Ctr of Arcold Brg
0427000015	15	11.21	40	40	L	R	356' E. of Heritage Ln
0427000015	16	11.57	35	20	R	L	100' E. of Bracketsss PT Rd
0427000015	17	11.66	35	20	L	R	At Green Trees Rd
0427000015	18	11.75	35	30	R	L	At Tanager Brg
0427000015	19	11.89	35	30	R	L	1250' E. of Green Trees Rd
0427000015	20	11.97	35	35	L	R	1676' E. of Green Trees Rd
0427000015	21	12.03	35	35	R	L	2000' E. of Green Trees Rd
0427000015	22	12.21	35	30	L	R	At 150' W. of Orono Orch. Rd

Table H-2: Speed limit zones along test route (heading west from Minneapolis to Orono)

TIS_CODE	BEG_PT	END_PT	LIMIT	DESCRIPTION
0100000094	232.234	236.938	55	BEG 6 LN I 394 TO HENN/RAM CL (236.319)
0100000094	231.244	232.234	55	BEG 4 LN TH 55 TO BEG 6 LN .1 MI E OF I 394
0100000394	0	8.772	55	I 494 TO BEG SL 40 I 94
0200000012	157.088	157.127	55	BEG SL 55 .2 MI W I 494 TO I 494 (156+01.014)
0200000012	152.859	157.088	65	BEG SL 65 CSAH 42 TO SL 55 .2 MI W I-494
0427000015	12.8	13.43	50	ORONO / WAYZATA CITY LIMITS TO RAMP TO LAKE ST. (OLD CSAH 15)
0427000015	12.54	12.8	50	FERNDALE RD. TO ORONO / WAYZATA CITY LIMITS
0427000015	12.37	12.54	50	ORONO ORCHARD RD. (765 FT. EAST FOR WB TRAFFIC) TO FERNDALE RD.
0427000015	12.33	12.37	0	ORONO ORCHARD RD. (480 FT. EAST FOR EB TRAFFIC) TO ORONO ORCHARD RD. (765 FT. EAST FOR WB TRAFFIC)
0427000015	12.23	12.32	35	ORONO ORCHARD RD. TO ORONO ORCHARD RD. (480 FT. EAST FOR EB TRAFFIC)
0427000015	11.32	12.23	35	BRACKETTS PT. RD. (1180 FT. WEST) TO ORONO ORCHARD RD.
0427000015	8.47	11.32	40	CSAH 19 (650 FT. EAST) TO BRACKETTS PT. RD. (1180 FT. WEST)
0427000015	5.64	8.47	35	BELMONT LANE (150 FT. EAST) TO CSAH 19 (650 FT. EAST)