Investigation of the Implementation of a Probe-Vehicle Based Pavement Roughness Estimation System

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16. Abstract

As roadway systems age and maintenance budgets shrink, a need emerges for timely and roughness data for pavement maintenance decision-making. The Virginia Department of Transportation (VDOT) maintains the third-largest state network of roadways in America, with $1.8 billion budgeted for roadway maintenance in 2012. Pavement assessment data in Virginia is currently collected by a contractor using a dedicated sensor platform. Frequency of collection is once per year on the interstate highway system and primary roadways, and once every five years for secondary roadways. Collected data is analyzed to produce indices which are the basis for pavement maintenance decision making.

This paper outlines a pavement roughness data gathering system using the connected vehicle program under the US Department of Transportation (USDOT)'s Intelligent Transportation Systems (ITS) initiative. The data-gathering system will increase frequency of pavement roughness data collection on primary, secondary, and interstate roadways, increase the number of lane-miles of monitored roadways, decrease lag time from collection to interpretation, and add to the information available to state transportation agency employees.

The technical feasibility and characteristics of three potential system structures are researched and discussed. All three systems use accelerometers and wireless communications to gather pavement roughness data, but differ in technology and approach. One uses ITS and connected vehicle technology, a second uses an installed accelerometer and communications system instrument package, and the third uses mobile communications devices containing accelerometers. The most appropriate system uses smartphone devices to gather data using integrated accelerometers and transmitting data using commercial wireless services.

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Chapter 1: Introduction

As paved roadway systems age and maintenance budgets shrink, a need emerges for more up-to-date pavement condition data on roadway networks. The Virginia Department of Transportation (VDOT) maintains the third-largest state network of roadways in the United States with a 2012 budget of $4.76 billion. Of this budget, 37% is budgeted for maintenance activities, with the remainder going for new projects, debt service, earmarks, and special projects [1]. Pavement assessment data is collected by VDOT once per year for the interstate highway system and primary roadways, and once every five years for secondary roadways. The data is collected by a VDOT contractor, Fugro, using a specialized vehicle platform and a suite of sensors. This condition data is analyzed to produce indices which serve as the basis for pavement maintenance decision making, and thus allocation and disbursement of the portion of the annual budget dedicated to pavement maintenance.

VDOT uses pavement deterioration indices derived from Fugro-collected pavement condition data, including a composite of two separate indices called the Composite Condition Index (CCI), and simple matrices to make pavement maintenance decisions as shown in Figure 1.1.

Maintenance Activity Category	**CCI Range**	
	Plant Mix	**Non Plant**
Do Nothing (DN)	> 85	>70
Preventive Maintenance (PM)	66– 85	56 – 70
Corrective Maintenance (CM)	49 – 65	41 – 55
Restorative Maintenance (RM)	≤ 48	<=40

Figure 1.1: Maintenance Activities for Secondary Pavements by CCI Range [2]

The matrices are comprised of roadway condition indices, type of pavement, and maintenance activities with associated life expectancies. Types of maintenance activities and associated costs are shown in Figure 1.2.

Activity Category	Exp. Life (Years)	Plant Mix*	Non Plant Mix**
Do Nothing (DN)	N/A	N/A	N/A
Preventive Maintenance	2 – 5	$6,105.35	$560.05
Corrective Maintenance	7 – 10	$52,732.10	$11,198.70
Restorative Maintenance	8 – 15	$102,957.20	$48,686.40

Figure 1.2: Cost per Mile for Maintenance Activity Categories, Secondary Pavements [2]

Examples of indices used for decision-making include the load-related distress rating (LDR), the non-load related distress rating (NDR), and CCI as described above. These indices are calculated using pavement distresses such as alligator cracking, rutting, and patching. In addition to visible pavement distresses, roughness measurements are collected and used to gain a picture of roadway condition and as a way to increase situational awareness to help with maintenance decisions [3]. Increasing the frequency of pavement roughness data collection could decrease lag time from data collection to useable information, and add to the total amount of information available to state transportation agency employees for the purposes of roadway maintenance.

Recent research indicates the potential for vehicle-based accelerometers installed in vehicles or contained within mobile communications devices to gather pavement roughness data [4]. In response, this paper investigates the use of a probe-vehicle based pavement condition data-gathering system utilizing Intelligent Transportation Systems (ITS) principles to supplement contractor-operated data collection vehicles. The system allows more frequent collection of road roughness data and an expansion of the number of covered lane-miles and networks; VDOT data collection currently covers only the right-most travel lane.

The US Department of Transportation (USDOT)'s ITS initiative is intended to introduce intelligent vehicles, infrastructure, and communications systems to the United States' transportation system. The core of the ITS program is the connected vehicle research program, which aims to connect vehicles, infrastructure, and mobile devices for safety, efficiency, and environmental improvements through wirelessly shared information. ITS primarily focuses on safety and efficiency improvements, but elements of the system have potential for use as data-gathering applications.

1.1 Impact and Motivation

The primary goal of the connected vehicle portion of the federal ITS program is to increase safety on roadway networks by increasing information available to stakeholders about traffic, weather, road conditions, and tolling systems. ITS' data-gathering capabilities may also be utilized for non-safety critical applications; once implemented, the program should prove a powerful tool for gathering data from mobile sources for a variety of applications. This paper explores the potential for the integration of a pavement roughness data gathering system with ITS, utilizing the data-gathering capability of the program and expanding possible uses for such a system.

Roughness data captured from contractor efforts may be years out of date for secondary roads, hampering VDOT's ability make accurate and timely pavement maintenance decisions. According to a personal interview with Affan Habib on July 15, 2011, approximately two weeks to one month would be the minimum period during which variations in pavement roughness may be detectable by measurement equipment for the purposes of identifying pavement wear trends, and thus the minimum time interval which would provide useful data for pavement maintenance programs.

Using probe vehicles to gather roughness data offers several advantages over the current, single-source data collection system. First, it allows more frequent updates of roughness data and coverage for an increased number of lane-miles on an annual basis. Second, the system could lower data gathering costs by either decreasing the frequency of VDOT contractor data collection or allowing tightly focused assessments when warranted as opposed to blanket coverage. Third, it will move probe-vehicle applications and research forward by demonstrating such applications are feasible in full-scale, real-world applications. Lastly, the system can allow more sophisticated and accurate pavement deterioration tracking; current methods depend on the use of pavement deterioration models to predict pavement condition between assessments [3].

There are also potential positive long-term secondary and tertiary benefits which accompany the implementation of such a probe-vehicle system. One such benefit is serving as a proof of concept for secondary applications of the connected vehicle program, adding value to the ITS program and maximizing return on USDOT's research funds and efforts. A well-planned and executed roughness data collection system can also serve as a proof-of-concept for other types of data-gathering systems; for example, an attempt to gather data on the effect of weather on vehicle dynamics or driver behavior.

1.2 Outline of Report

This report consists of 6 chapters, as follows:

1. **Introduction –** Introduction to the topic, impact, and motivation for research.
2. **Background –** Provides an overview of topics addressed in this paper
3. **Literature Review** – State of the practice in several relevant subject areas
4. **Analysis of Alternatives** – Analysis of technology and implementation options
5. **Concept of Operations –** Outlines system characteristics from user viewpoint
6. **Conclusions –** Offers conclusions of the research and suggested future research topics

Chapter 2: Background

The background section of this document provides a functional understanding of pavement condition assessment, intelligent transportation systems, the connected vehicle program, and current pavement condition data gathering techniques. First, a brief history of pavement condition assessment illustrates the rapid progress in the area of transportation engineering over the past 40 years, and how the proposed system integrates with the system. Second, current pavement assessment practices are described to illustrate how specific characteristics of the current pavement maintenance decision-making system may be improved upon by a new source of roughness data. Lastly, ITS and the connected vehicle program are described in detail; an understanding of these systems are integral to a discussion of how the new system will integrate into current and planned system capabilities.

2.1 History of Pavement Condition Assessment

Pavement condition assessment is generally defined as the assessment of paved roadways for the purposes of gauging level of service and choosing the appropriate maintenance practices associated with a section of pavement [5]. To underscore the importance of pavement assessment data in the budgeting and maintenance process, a brief history of pavement condition assessment by VDOT is presented here. Prior to the implementation of a formal pavement management system in Virginia, pavement management was conducted in an ad-hoc, budget-driven (as opposed to results-driven) process. The first effort at a pavement management system began with the construction of a pavement inventory database during the 1970s. Construction records outlining the depth of subbase, material, dates, and corrective action were consolidated into the Highway Traffic Records Information/Inventory System (HTRIS), which was replaced by the current Pavement Management System (PMS) in approximately 2008 [3].

The need for a formal pavement management system became clear in the late 1970s, and was articulated by a 1981 research paper [5]. Following this paper, a flexible pavement condition rating procedure was developed to allocate funds among districts and counties in the state of Virginia. The basic element of this condition rating procedure was a “windshield survey” conducted by a VDOT employee and based on visual measurement and evaluation of surface distresses. This condition rating was called the distress maintenance rating (DMR). The DMR was compiled by subtracting points from a possible 100 according to varying degrees of surface distress as noted by a technician. The DMR did not include a quantitative ride quality rating; however, a subjective rating was used to differentiate between pavements with similar DMR values.

The DMR and windshield survey method were employed until the early 1990s, when the safety and precision of the method were questioned by VDOT, pavement researchers, and other transportation departments. The method was subjective, and consistency across maintenance districts was relatively poor when compared with modern automated methods. A standard existed for the number of points subtracted for each type of distress, but some of the work depended upon the technician’s subjective rating of the severity of certain types of distresses according to parameters such as average crack length, depth, and type of cracking. The best quality control process available at the time consisted of separate survey teams evaluating overlapping stretches of pavement and comparing results. The system distributed maintenance funds based on DMR values gathered during the previous or current fiscal year, and had no integrated optimization capabilities. The system was not developed for planning maintenance out over more than one year, and by definition maintenance decisions were often oriented towards immediate needs rather than for optimum cost or results over a medium or long term time horizon.

In response to demand for increased robustness, consistency, and longer-term planning assistance and capabilities, several new indices and a video-based assessment system were developed in the 1990s. The new system was based on the three indices outlined in Chapter 1: LDR, NDR, and CCI. CCI is simply calculated as the lower of LDR and NDR. This video-based method used pattern recognition software to analyze distresses presented in video images of the roadway surface, leading to improvement in two areas: consistency and safety. Data consistency was improved by limiting subjective visual scans increasing the accuracy and objectivity of surface distress measurement. Eliminating windshield surveys improved safety as well; surveys often involved driving slowly on the shoulder of major thoroughfares, exposing workers to high-speed traffic. The video-analysis method also allowed coverage of significantly more lane-miles of pavement per year. Due to contractor difficulties, windshield surveys resumed in 2000 and were used until 2006; the current automated methods conducted by a contractor were implemented in 2007 [3].

The same three indices are currently used in VDOT's maintenance decision-making processes alongside improvements in optimization using the PMS, data collection, and analysis. The current system relies on advanced computing technology and a multitude of sensors (including lasers and accelerometers) to collect rutting, cracking, roughness, texture, and surface distress information for translation into the three indices. The current contractor for VDOT is Fugro, which provides a turn-key solution for the collection and analysis of pavement condition data. Fugro's digital cameras record images for later analysis by a software package known as WiseCrax, which produces indices from the information. Fugro Roadware vans are equipped with sensors which capture road roughness, which is recorded in inches of vertical deviation per mile according to the International Roughness Index (IRI).

Figure 2.1.1: Fugro Collection Vehicle [6]

Figure 2.1.2: Interior of Fugro Vehicle [7]

In addition to collecting IRI and distress data for use in computing LDR and NDR, Fugro vans are equipped with forward-looking cameras to collect images of infrastructure such as stop signs, guard rails, and obstructions to roadway sightlines. Images captured by the collection van are combined with pavement condition indices on a single screen to allow VDOT employees good situational awareness of the condition of the roadway network [3]. The equipment and expertise required to collect pavement condition data comes at a price; in an interview on June 10, 2011, Raja Shekharan of VDOT estimated the current costs for this service to be $1.8 million per year.

2.2 Calculation of IRI

VDOT uses IRI as the pavement roughness measurement standard, as do many state Departments of Transportation (DOTs). IRI is recorded in inches per mile (in/mile) and is defined by the American Association of State Highway and Transportation Officials (AASHTO) and the American Society of Testing and Materials (ASTM), and these agencies outline the equipment and calculation techniques required. The quarter-car simulation model mandated by the ASTM for calculation of IRI uses physical movement and resistance relationships to evaluate the movement of one wheel, tire, and suspension system; hence the “quarter car.” The essential physics of the quarter-car model involve two masses (vehicle and wheel/tire/axle) and two springs (tire and the suspension). This model is the basis for calibration of response-type roughness measuring equipment and provides “a means for evaluating traveled surface-roughness characteristics directly from a measured profile [8].” The model provides calibration numbers for the accelerometers by evaluating the response of a vehicle to a specific type or amount of surface roughness and uses these values to calculate roughness based on vehicle accelerations.

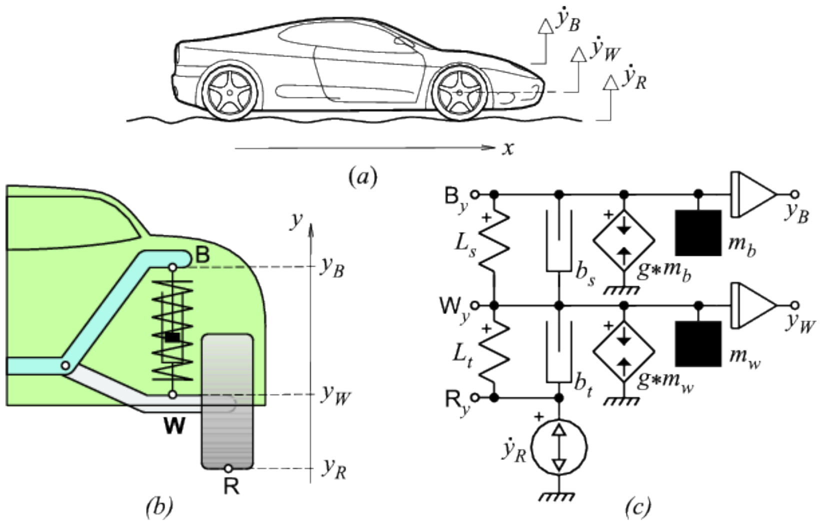

Figure 2.2.1: The Quarter-car Simulation Model [9]

ASTM publication E950-9 covers the process for “the measurement and recording of the profile of vehicular-traveled surfaces with an accelerometer-established inertial reference on a profile-measuring vehicle [10].” The manual for the Highway Performance Monitoring System (HPMS), a national database of roadway information kept by the Federal Highway Administration (FHWA), dictates a roughness measurement procedure in accordance with the AASHTO Standard Practice for Determination of International Roughness Index for Quantifying Roughness of Pavements, AASHTO PP 37-04. The HPMS manual also gives guidelines for collection of roughness data, including collecting data when pavement is stable (not in a freeze/thaw or wet state), collecting in the outside lane when practical, maintaining constant speeds, and excluding the impacts of bridges, railroad crossings, or other road features which are not representative of the overall roadway [11].

2.3 Pavement Condition Assessment

The transportation industry uses a number of metrics for the evaluation of pavement condition in support of maintenance and infrastructure management. VDOT decisions regarding pavement maintenance are primarily based on CCI. For the evaluation of flexible pavement, two separate indices are compiled, namely LDR and NDR. LDR is composed of alligator cracking, wheel path patching, and rutting, while NDR is based on longitudinal and transverse cracking, non-wheel path patching, and bleeding. The lower of these two indices becomes CCI. VDOT uses indices for different types of pavement; for example, continuously reinforced concrete and jointed concrete pavement use the concrete distress rating (CDR) and the concrete punchout rating (CPR).

VDOT collects roughness measurements on pavement surfaces throughout the state roadway network for left and right wheel paths, the average of both wheel paths, and use of the quarter-car simulation model as described above. VDOT measurements conform with ASTM standard E950-9 and the HPMS Field Manual for Class II profiling requirements. Road roughness information collected by the proposed probe-vehicle system would be estimates of IRI, as collection methods would not conform to current standards. IRI is not a component of CCI and is not used within the PMS in a direct capacity [3]. According to a personal interview with Affan Habib of VDOT on July 15, IRI is a required component of VDOT's annual report to the FHWA as part of the HPMS, and is required to receive federal funding for construction and pavement maintenance projects. IRI is also used for overall awareness of road condition for VDOT decision-makers and awarding contractor payments according to final project roughness readings. The current pay adjustment chart based on IRI can be found in Figure 2.3.1 below:

TABLE B - NON- INTERSTATE SYSTEM	
IRI After Completion (In/Mile)	**Pay Adjustment (% Unit Price)**
55.0 and Under	115
55.1-65.0	110
65.1-80.0	100
80.1-90.0	90
90.1-100.0	80
100.1-110.0	70
110.1-130.0	60 or Subject To Corrective Action
130.1-150.0	40 or Subject to Corrective Action
150.1-170.0	20 or Subject to Corrective Action
Over 170.1	0 or Subject to Corrective Action

Figure 2.3.1: IRI to Pay Adjustment Chart on Secondary Roads [12]

2.4 Pavement Data Collection

Current VDOT pavement data collection methods utilizing Fugro vehicles cover the interstate system and primary roadways and approximately 20% of high-volume secondary roads per year, resulting in VDOT possession of accurate data on secondary roadways once every five years. Processing, cross-checking for consistency, and data storage mean up to six months may be required after collection before pavement condition indices reach appropriate VDOT decision makers [4]. Pavement maintenance decision matrices require accurate pavement condition indices, and the lack of timely (within several years) pavement condition data can lead to inefficiencies in the selection of maintenance methods, timing of repairs, or disbursement of funds for repairs.

The first requirement for an effective asset management system as outlined in the International Infrastructure Maintenance Manual (IIMM) is knowledge of existing assets, followed by knowledge of current asset condition and assessment of level of service provided by the those assets [13]. Near real-time knowledge of pavement roughness would allow identification of the level of service for customers; in this case, Virginia roadway users. VDOT uses a "Dashboard" displayed prominently on the VDOT website to keep track of level of service metrics including, somewhat ambiguously, a measurement of the "Condition" or "Quality of Road Service" which includes "ride quality" and "pavement condition" subcategories.

Increasing the frequency of data collection using current methods would increase the recurring expense for Virginia taxpayers. In today's budget-sensitive climate, increasing costs for data collection is politically impractical. Allowing decision makers to collect increased amounts of data at low additional cost would provide substantial benefits in the form of enhanced roadway condition awareness and increased accuracy in pavement maintenance decisions.

2.5 The Connected Vehicle Program & ITS

Any pavement roughness data collection system will require integration with future or existing probe vehicle or infrastructure-based collection and communications systems. One such system is USDOT's ITS program. The program focuses on "intelligent vehicles, intelligent infrastructure, and the creation of an intelligent transportation system through integration with and between these two components [14]." Several components of the connected vehicle system, including on-board vehicle sensors and wireless transmission capability, have potential for use in collecting pavement condition data which can be used to make informed decisions on roadway maintenance and life-cycle assessment. Other ITS options include the installation of an instrument package containing dedicated accelerometers and communications equipment in agency-owned vehicles, or use of a mobile communications device containing internal accelerometers. Researchers are evaluating the feasibility of these types of systems [4]; their efforts are outlined and analyzed in subsequent sections.

The connected vehicle program is primarily intended to address safety, which is stressed throughout the program's description and mission. The ITS initiative, and by association the connected vehicle program, aims to equip vehicles and infrastructure with data collection sensors and link them with information systems which can interpret and respond to changing traffic and roadway conditions to maximize efficiency and safety. Applications may include variable speed limits and driver warnings for preventing accidents on highways, systems which warn drivers when it is unsafe to pass on two-lane roadways, enhance blind spot awareness by signaling a warning, and a number of other safety and efficiency improvements [15].

There are two basic communications components to the connected vehicle program: Vehicle to Vehicle (V2V) communications and Vehicle to Infrastructure (V2I) communications. V2V uses information contained in a wireless message transmitted from vehicle to vehicle, and helps prevent crashes and injuries by activation of warnings for the driver or other vehicle safety systems. For example, if two vehicles are following closely and the lead vehicle suddenly brakes in response to a roadway obstruction, the following vehicle will be notified through a safety message, and vehicle systems such as emergency braking or airbags will be activated if necessary.

V2I communications require road-based infrastructure, and involve communications from vehicles to fixed-position devices which are in turn connected to a network or the internet. The V2I system is primarily concerned with intersection safety, the collection of information from vehicles for analysis, and producing driver advisories and warnings to increase the efficiency and safety of existing infrastructure. Figure 2.5.1 provides an illustration of the basic structure behind V2I and V2V communications.

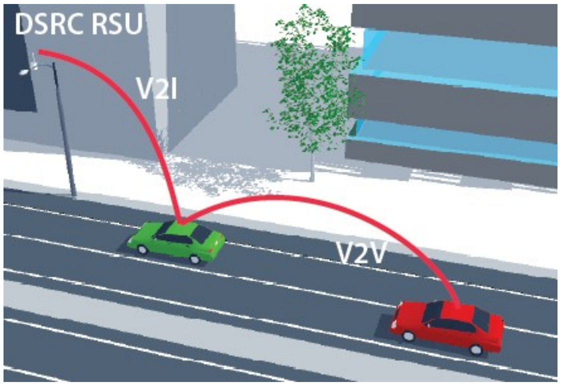

Figure 2.5.1: Illustration of V2V and V2I [16]

The operational and hardware elements of V2V and V2I systems consist of a vehicle on-board unit (OBU), a roadside communications unit (RSU), and a dedicated short-range communications system (DSRC) which allows the wireless transmission of data over distances of less than 1,000 meters. In literature and published information, OBUs may also be referred to as on-board equipment (OBE), and RSUs referred to as road-side equipment (RSE).

Figure 2.5.2: Example of an RSU [16]

Although multiple wireless short-range communications protocols such as Bluetooth, IEEE 802.11, and WiFi are currently in use, DSRC refers specifically to V2V and V2I communications in the 5.9 GHz frequency range. At the request of the US Department of Transportation (USDOT), a 75 MHz portion of the wireless spectrum (5.850-5.925 GHz) was set aside in October of 1999 by the Federal Communications Commission (FCC) specifically for use by ITS. Dedicated bandwidth is essential to research and development of ITS, as it greatly decreases competing signals from other wireless devices and enhances the safety and security of the system. Increased signal reliability and security from competition in the dedicated range allows for more effective use in time critical safety-related applications [17].

The pavement roughness data gathering application of ITS is derived from the V2I component of ITS. The stated primary goal of the V2I program is defined by the USDOT Research and Innovative Technology Administration (RITA) as “the wireless exchange of critical safety and operational data between vehicles and highway infrastructure… V2I communications apply to all vehicle types and all roads, and transform infrastructure equipment into ‘smart infrastructure’ through the incorporation of algorithms using data exchanged between vehicles and infrastructure elements to perform calculations that recognize high-risk situations in advance [18]." Another goal of the program is to "to support infrastructure and vehicle deployments," which closely reflects the goals of the system as defined in this paper [19].

"Smart infrastructure" as defined by the USDOT is primarily concerned with safety, but proposed V2I infrastructure has sufficient capacity for low-priority wireless transmissions from vehicles such as headlight status, temperature information, electronic payment processing, tire pressure, steering wheel angle, throttle position, and accelerometer readings [20]. This type of information can be aggregated and used by USDOT for a variety of decision-making purposes.

2.6 J2735 Message Set Operations

Active safety elements of the connected vehicle program depend on standardized communications between vehicles using DSRC. The Society of Automotive Engineers (SAE) has published a document which outlines the methodology for V2V and V2I vehicle communications: the J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary. A review of J2735 indicates the connected vehicle system is designed for quick "snapshots" of information at relatively low transmission latencies and over short distances. The design is intended to ensure the ability of the system to transmit safety-critical information while not overloading the frequency range in dense traffic situations. Considerable effort has been expended to limit and standardize information to minimize the total amount of information transmitted via DSRC.

Within J2735, DSRC messages are classified in one of three categories; those requiring a latency of < 10ms, 10-20ms, and >20ms. In general, these categories reflect safety of life, public safety, and non-priority messages, respectively. Lower-priority messages are sent according to a defined message set hierarchy.

The building block of ITS safety systems according to J2735 standard message set is the basic safety message (BSM,) which is a pre-determined set of elements critical for safety use. Sometimes described as the “Here I Am” message, the BSM contains data from vehicle sensors at an instant in time, and includes information on vehicle position, speed and acceleration, yaw rate, brake status, and vehicle specifications. The broadcast interval varies with speed or roadway conditions; by default the BSM is broadcast every 0.1 second (100 ms or 10 Hz). The broadcast is unilateral, takes place in the presence or absence of other vehicles or RSUs, and does not re-broadcast if packets of information are lost or damaged. No BSM information is stored on the OBE; the message is intended for reception and immediate interpretation by nearby vehicles or RSUs [21].

A second tier of messaging described in J2735 is a “snapshot” of vehicle information, known as Probe Data, from vehicle OBE to RSU. Probe Data contains a greater number of data elements than the BSM and is stored on the vehicle’s OBU prior to uploading to the next available RSU. Probe Data is intended to provide a picture of current traffic and weather conditions from vehicle data. Probe Data consists of 43 data elements, including data such as tire pressure, wiper rate, exterior lights, and coefficient of friction between tires and the roadway in addition to BSM information. Probe Data is generated on a recurring basis, and may be triggered according to a pre-determined time interval or a specific event such as a hard stop.

The J2735 standard calls for vehicle OBEs to store at least 30 snapshots of Probe Data, giving vehicles the ability to collect situational data between RSU connections. The default snapshot capture method is a varying time scale based on vehicle speed. For example, a rural case is given in J2735 in which RSUs are 10 miles apart, or 10 minutes based on a vehicle speed of 60 miles per hour. In this case, the Probe Data snapshot interval would be 20 seconds, for a total of 30 snapshots captured in the distance between the two RSUs. For the urban case given in J2735, RSUs are placed at a 2/3 mile interval; based on an assumed vehicle speed of 20 miles per hour the vehicle OBE will store 30 snapshots by the time it is within range of the next RSU [20].

Chapter 3: Literature Review

The literature review portion of this paper provides an overview of the state of the art in theoretical and practical areas pertaining to the proposed data-gathering system. The review includes several functional areas addressed during system design and implementation, including pavement condition data collection, mobile and remote sensor networks, vehicle-based sensors, and the use of mobile devices as data probes.

The first functional area, pavement condition data collection, uses dedicated vehicles equipped with sensors and advanced computing technology, and should be understood before investigating the added capabilities offered by the proposed system. Second, a review of the design and use of previously implemented roadway maintenance data-gathering sensor networks yields insight into the current state of technology and the integration of such systems into maintenance and governance strategies for roadways. Third, recent experimental and test deployment results from vehicle-based sensor networks provide a look at issues unique to vehicle-based sensor deployment. Lastly, the review covers current work in the use of mobile communications devices in gathering pavement roughness data.

3.1 Sensor Networks for Maintenance Decision-Making

The pavement assessment application of the connected vehicle program depends on using individual probe vehicles equipped with sensors to gather and transmit data to infrastructure-based systems for aggregation and use by a governing entity for decision-making purposes. The sensor-network concept has been researched and deployed in support of other types of decision-making, including time-critical weather-based maintenance. Most notably, a body of research exists for the use of probe vehicle and fixed infrastructure data-gathering to support extreme weather event road maintenance response. In general these systems are effective and helpful for decision-making, but as of July 2011 no *vehicle*-based sensor stations have been deployed. Some systems do depend at least partially upon audio or data reports from offsite employees utilizing handheld sensors, or the reporting of empirical observations.

In 2006 the Maine Department of Transportation (MDOT) tested a program known as the Maintenance Decision Support System (MDSS) to support roadway maintenance decision making during extreme weather events, most notably winter weather. In contrast to a vehicle-based probe data system, the MDSS system utilized manually operated sensors; however, the decision-making protocol and mobile nature of data collection are similar to a deployed pavement data-collection system. MDSS incorporates several tools, such as pavement frost and weather forecasts, traffic volume information, available roadway and weather information, and the effects of previous roadway treatments into a single decision-making software program [22]. MDSS relied primarily on personnel using handheld sensors to obtain data such as pavement temperature; this task could be automated and connected with data collection and communications systems within the connected vehicle program. These systems utilized fixed-position sensors in addition to personnel-based reporting and thus do not provide a direct comparison with probe-vehicle based data gathering, but the implementation data they gathered has proven valuable. A similar system installed in Utah in 2004 resulted in estimated maintenance savings of $2.2 million/year, for approximately 18% of 2004-

2005 system installation and maintenance cost. The estimated cost/benefit ratio of installing such a system is 10:1 [22].

The Road Weather Information System (RWIS) is a fully deployed system which shares significant similarities with a potential probe-vehicle based data gathering system. The RWIS is made up of numerous Environmental Sensor Stations (ESSs), wireless communication systems, and a central software platform for synthesis and analysis of incoming information. This configuration is similar to the system configuration of the envisioned ITS system, which is made up of infrastructure sensors, vehicles, and a central processing center [23]. The RWIS uses environmental sensors to transmit location-based weather information to a processing center, where it can be used to make real-time roadway maintenance decisions for weather events. An FHWA initiative known as *Claris* uses deployed weather sensors, data from Doppler radar, and observations to achieve useful air and pavement temperature forecasts [24]. The probe-vehicle application aims to use near-real time roughness information to make long-term pavement maintenance decisions, a logical extension of current practice.

3.2 Vehicle-Based Sensors

Researchers in the ITS field are developing and testing vehicle-based weather sensors to replace or supplement fixed-position sensors. In a 2007 case study the consulting firm Noblis equipped a fleet of vehicles with GPS locating devices, air temperature sensors, and infrared pavement temperature sensors. The objective of the case study was to analyze the effects of sensor placement, vehicle speed and thermal characteristics, and weather on the accuracy of vehicle-based temperature measurements.

Approximately 70 test runs showed significant differences in the biases of similar vehicles, with differences in bias more pronounced during cold weather and larger bias variability in the summer [25]. These results do not preclude the use of vehicle-based sensor applications in the future, but do foreshadow difficulties with probe-vehicle sensor platforms and may indicate the need for extensive statistical analysis before deployment of similar probe-based data gathering systems.

The FHWA Road Weather Management Program has identified a number of vehicle sensor outputs which can be captured by the V2I component of ITS and used to determine roadway weather conditions. These outputs include ambient temperature, vehicle speed, heading, atmospheric pressure, windshield wiper settings/rain sensor output, steering wheel angle and rate of change, ambient noise levels, and traction control/ABS sensor outputs. For example, a combination of accelerometer data, vehicle speed, heading, and steering wheel rate of change may potentially be used to capture wind speed and direction [26]. Sun sensors and driver assistance systems like adaptive cruise control may also provide information which can be used to construct a picture of weather and traffic conditions on roadways.

The most applicable work in the vehicle-based sensor field was recently completed by Auburn University and outlined in *Investigation of Pavement Maintenance Applications of Intellidrive^SM (Final Report): Implementation and Deployment Factors for Vehicle Probe-based Pavement Maintenance (PBPM)*. The goal of Auburn's research was to prove the technical feasibility of capturing usable roughness data from vehicles with internally installed accelerometers. The research involved several steps: 1) collection of roughness data using an accelerometer-equipped test vehicle on a closed test track, 2) transmission of data using DSRC devices operating in the 5.725 to 5.875 MHz range from vehicle to infrastructure, 3) transformation of data from time domain to a scalar signal, and 4) conversion of data into usable roughness information, predominantly through comparison with IRI values. The first two steps are most applicable to this paper, and thus will be addressed in the most depth.

Auburn researchers installed a six-axis (x, y, and z vertical motion, plus pitch, roll, and yaw motions) Crossbow 440 inertial measurement unit (IMU) accelerometer in the armrest of an Infiniti G35 test vehicle. Additional components included a Novatel Propak-v3 GPS receiver to provide coordinates and a Kapsch multi-configurable networking unit (MCNU) to allow wireless communications with fixed-position MCNUs by the test track emulating RSUs. These components were linked to a Linux-based laptop computer equipped with data recording software.

Following the installation of the components, the test vehicle was driven on an approximately 2,700 meter test track containing sections of pavement with varying IRI measurements. Multiple test runs were conducted at speeds of 40, 50, and 60 miles per hour to simulate actual roadway conditions, and the collected data transformed into IRI estimates using the quarter-car model and mathematical methods. The results of the study indicated that the application of the root mean square method to vertical acceleration produces an estimate of IRI which, assuming a Gaussian error function, is plus or minus 0.246 meters per kilometer (16.1 inches per mile) on a 95% confidence interval. By way of comparison, IRI on the test track approximately ranged from below 1 to above 3 meters per kilometer [4], and pavement defined as being in “good” condition by VDOT is between 60 and 100 inches per mile (0.95 to 1.6 meters per kilometer) [27].

One challenge when obtaining road roughness calculations from vertical accelerations is variation in vehicle speed. The frequency of vertical deviation inputs to the system changes according to vehicle speed, as do peak acceleration values. The difference between frequency and total acceleration values must be compensated for to provide a meaningful estimate of roughness at a wide variety of roadway speeds. Auburn researchers derived an equation to compensate for vehicle speed which divides acceleration values by longitudinal speed, resulting in standardized IRI estimate output. Another challenge is the variation of response by vehicle sensors to identical roadway surfaces based on differences in suspension, vehicle mass, wheel/tire/axle mass, spring rates, and other factors. IRI output for acceleration inputs need to be calibrated for individual vehicles, and best results are obtained after multiple calibration runs [3].

3.3 Mobile Devices as Data Probes

Moving forward from dedicated connected vehicle infrastructure, the market saturation and widespread acceptance of internet-enabled smartphones presents an attractive opportunity for mobile data collection. The collection and transmission of road roughness data to VDOT or other governing entity through existing communications networks is an alternative to equipment and cost-intensive dedicated infrastructure. Mobile phones from manufacturers such as Samsung, Nokia, HTC, LG, Motorola and Apple contain accelerometers to enhance functionality; examples include a music player which uses a shaking motion to advance music tracks and trigging an exchange of contact information after two phone users “bump.” These applications predominantly use a specific g-force threshold to trigger actions rather than the full capabilities of internal accelerometers. When used to their potential, these accelerometers can provide useable information on road roughness.

The University of Michigan Transportation Research Institute (UMTRI) is has developed an application for the Android mobile operating system which utilizes internal phone accelerometers to capture road roughness data. The application also uses the phone's Bluetooth capabilities to receive information from the vehicle's On-Board Diagnostic port, or OBD, through a Bluetooth-enabled transmitter.

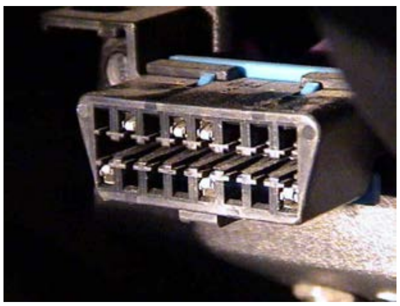

Figure 3.4.1: Vehicle OBD II Port [28]

Figure 3.4.2: OBD Bluetooth Interface [29]

Information available from the OBD port varies from vehicle to vehicle based on manufacturer specifications, but commonly includes at least vehicle speed, engine speed, and feedback from select engine sensors [30]. The application also interfaces with other sensors through Bluetooth; examples include pavement temperature and atmospheric pressure sensors. Accelerometer, GPS, vehicle speed, and other data is sampled by the application 100 times per second, converted to an Excel file, and uploaded via a 3G cellular network on a five-minute time cycle. This cycle repeats until the application is disabled, and the application starts concurrent with vehicle ignition.

Research involving this application is on-going; it has not yet been released to the Android Market application store, nor has a research paper been published. However, a personal interview with ITS research scientist Ralph Robinson on June 2, 2011 yielded useful information on the development process. The project is co-sponsored by the Michigan Department of Transportation (MDOT), and research is currently focused on correlating accelerometer readings captured by Android-based devices with a 10-point scale known as the Pavement Surface Evaluation and Rating (PASER) system.

The PASER system is used by MDOT to rate roadway condition as one of three condition ratings based on visual cues: good, fair, and poor. The equipment used for the PASER survey included a laptop, a GPS system, and simple data collection software. The data collection software allows the user to enter the number and relative frequency of observed surface distresses, which is used to rate the condition of the pavement. The subjective nature of this method, despite annual recurrent training and conducting the survey only during ideal conditions, means data is inherently less quantitative and objective than alternative methods of pavement condition rating [31]. Correlating roughness data with the PASER system is notably different from research work at Auburn University, which attempts to correlate road roughness with a more quantifiable measure of road roughness and pavement condition, IRI.

Chapter 4: Alternatives Analysis

This section of the paper analyzes three separate system designs for meeting system requirements, objectives, and goals as outlined in the Concept of Operations in Chapter 4. Analysis of individual approaches is presented, and technical topics relevant to all three alternatives are discussed. This document is intended to provide analysis of each method, a discussion of technical topics relevant to the three approaches, and eventual selection of one of the methods for implementation by VDOT. Each method is analyzed in four areas:

1. **Technical feasibility.** This section analyzes the technical and hardware requirements for implementation of the system as outlined.
2. **System performance.** This section compares system performance to preferred capabilities or to VDOT requirements for data-gathering.
3. **Integration/Installation.** This section briefly discusses the difficulty of system integration with current systems, or difficulties involved with installation.
4. **Cost.** A rough cost estimate allows the decision-maker or stakeholder to compare capabilities outlined in the previous two sections with a final cost.

These three system design approaches were derived from ongoing research. The connected vehicle or ITS approach is the original subject of this paper, the fleet vehicle method was derived from research being conducted at Auburn University, and the mobile device method was derived from research being conducted at the University of Michigan

Transportation Research Institute. These three approaches are outlined in general terms and defined below:

Connected Vehicle: This method uses OEM-installed accelerometers, sensor hardware and standardized on-board vehicle processing, storage, and communications equipment as described in the SAE J2735 DSRC Message Set Dictionary to gather and transmit roughness data. Transmission is accomplished using DSRC equipment to communicate with RSUs, which transmit data to a central location for aggregation and use.

Fleet Vehicle: This method collects roughness data through installation and calibration of semi-permanent, non-stock accelerometers in a fleet of agency-owned vehicles, supplemented by GPS units for positional information. Wireless communications, such as DSRC, Wi-Fi, or a commercial wireless carrier, provide data transmission services.

Mobile Device: This method uses accelerometer-equipped mobile devices, such as smartphones, to gather and transmit roughness information to a central database for interpretation, aggregation, and use.

4.1 Connected Vehicle Approach

The connected vehicle approach was developed in response to the USDOT's connected vehicle program, and is based on the standardization of future vehicle communications technology as outlined in the ITS program vision and SAE J2735. In this approach, accelerometers, sensor hardware and standardized on-board vehicle processing, storage, and communications equipment are utilized to gather and transmit roughness data to RSUs using DSRC equipment.

In summary, the approach proves technically difficult in the current configuration of the connected vehicle program. However, if changes to SAE J2735 standards or political changes (incentives for vehicle manufacturers to participate) allow system implementation, the approach displays conformity with roughness data-gathering requirements and is cost effective. A system diagram is presented below in Figure 4.1.1.

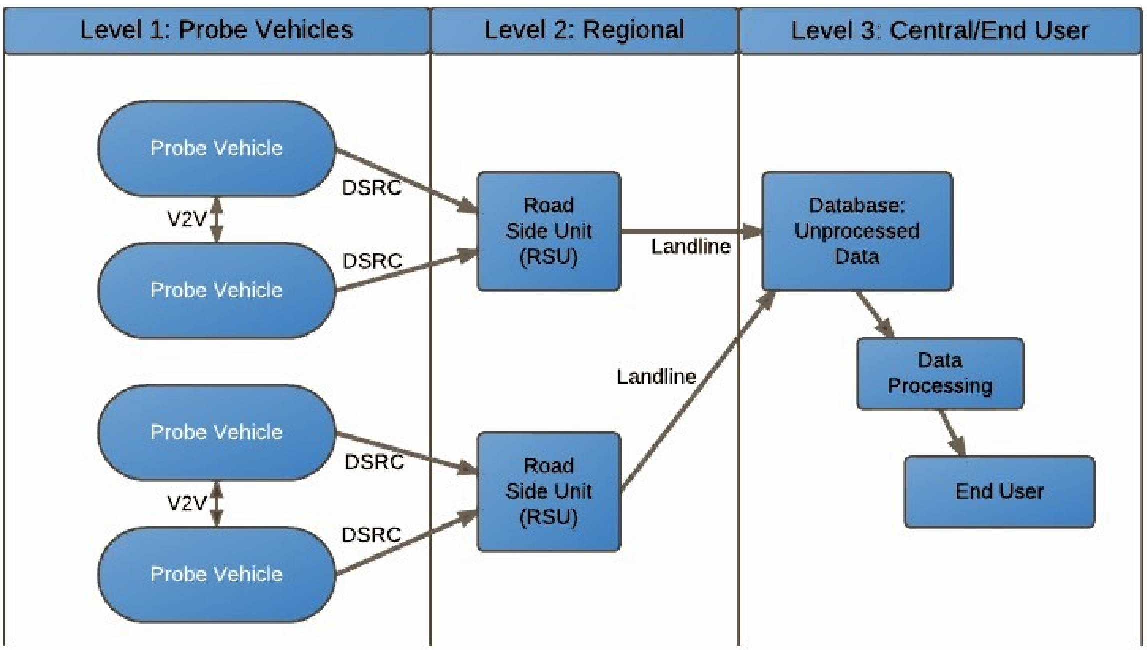

Figure 4.1.1: System Diagram of the Connected Vehicle Approach

4.1.1 Technical Analysis

Analysis of the connected vehicle approach shows several issues which require technical solutions prior to implementation. First, OEM accelerometers can be difficult to harvest data from, are not standard across vehicle models, and require individual assessment and calibration for each make and model of vehicle. Second, the SAE J2735 standard, combined with VDOT requirements for roughness data collection, places restrictions on the ability of vehicles to capture vertical acceleration information at a sufficiently high sampling rate to produce usable roughness data. Third, the transmission of roughness assessment data using DRSC is difficult due to large file sizes, high vehicle speeds, and range restrictions on current communications equipment.

Accelerometers

The J2735 approach uses sensor output from accelerometers installed in vehicles by original equipment manufacturers (OEMs). Modern vehicles contain these sensors in multiple systems, including airbags, dynamic performance enhancement systems, and rollover protection systems. Dynamic performance enhancement systems, also known as electronic stability control (ESC), use accelerometers to compare driver intentions (steering wheel angle input) with actual vehicle path to determine lateral motion, which the ESC system uses to apply braking to the appropriate wheel. Rollover protection systems also use accelerometers and are present in many modern SUVs and light trucks, including the Toyota Tundra and the Ford F-150 [32]. These systems detect when a rollover is imminent using vertical accelerometers and in some vehicles a lateral-motion accelerometer, and deploy safety systems as necessary [33].

Automotive accelerometers are predominantly of the micro-electromechanical systems (MEMS) variety. These sensors monitor electrical capacitance change due to accelerative force to generate a measure of g force and transmit a signal containing the information [34]. MEMS accelerometers vary in quality, accuracy, range of g force capacity and application. For example, sensors used in ABS systems meet certain minimum requirements such as a less than 1% sensitivity drift over the automotive range of operating temperatures (-40 degrees F to 125 degrees F), +/- 3% in initial accuracy, and have a dynamic range of +/- 1.5 g. By contrast, rollover detection sensors have a dynamic range of +/- 6 g and lower standards for both initial accuracy (+/- 10%) and sensitivity drift over operational temperature ranges (+/- 3%) [35]. In future vehicles equipped with OBEs and other J2735-compliant equipment, accelerometers will be interfaced to output vertical acceleration to the vehicle's OBE in the form of data element "DE_VerticalAcceleration" in increments of .02 g and over a +1.5/-3.4 g range.

Currently, significant challenges are associated with capturing useable data from OEM accelerometers. First, MEM accelerometers vary in sensitivity, accuracy, and signal output, leading to inconsistent quality across various vehicle manufacturers. The lack of standardization requires a vetting process to ensure consistent data quality and readings. Second, data generated by accelerometers may not be easily accessible outside of the vehicle subsystem the sensor was originally intended to service. While data is available through various vehicles' Controller Area Network (CAN) databus, arrangements must be made with OEMs on an individual basis, and J2735 standards have not yet been implemented to provide OBE standardization [3]. Lastly, accelerometer data may be affected by sharp turns, sudden accelerations, fluctuations in ambient temperature, and roadway conditions (icing, snow, etc.). This data quality concern may be partially mitigated by collecting roadway information with other probe-data sensors and flagging data with a warning if adverse conditions exist.

Accelerometer Calibration

As discussed in the background section, researchers at Auburn University have investigated the feasibility of calculating IRI using output from vehicle-based accelerometers. Auburn's research has focused on developing algorithms which can be used to generate accurate roadway roughness information from accelerometer readings. This research has been successful in correlating road roughness captured by accelerometers to IRI, but has also uncovered several challenges which must be addressed before useable readings are obtainable [3]. These challenges include the need for device calibration to individual vehicle dynamics to determine correlation with road roughness indices.

Data Capture

One technical challenge associated with the J2735 approach involves the proposed connected vehicle system outlined in J2735; the system is designed for broadcasting quick "snapshots" of information at low latencies and over short distances, and these snapshots limit accelerometer data collection to the snapshot interval outlined in J2735. The BSM is broadcast every 0.l seconds and contains an accelerometer reading, but is not stored on the OBE. Probe Data, which is recorded by the OBE, is collected on a variable time interval ranging from less than two seconds to over 20 seconds. VDOT requires a 6 inch collection interval for roughness readings [4]. To collect data to VDOT standards, OBEs would need to store 105,600 snapshots over a 10 mile stretch of roadway, or 7,000 snapshots over 2/3 mile. The J2735 standard currently requires vehicles to store 30 snapshots between RSU upload zones.

This standard, combined with potential flash memory storage shortages, precludes the collection of pavement data collection. For a vehicle traveling at 60 mph (88 fps), a 0.1 second interval is equivalent to capturing sensor information every 8.8 feet. In order to achieve a 6 inch measurement interval, a snapshot would have to be stored every $1/176^{th}$ of a second, or approximately 5 ms. At a 5 ms resolution, 10 miles of roadway will generate approximately 120,000 snapshots. Using the BSM snapshot size of 39 bytes, 120,000 snapshots will generate 4.5 megabytes of information. Capturing only accelerometer, GPS, and speed information through an "a la carte" (ACM) message may reduce data load; at an estimated 20 bytes of data and a 5 ms interval, 10 miles of roadway will generate 2.3 megabytes of data.

Vehicles could potentially upload rapid snapshots of information while within range of an RSU; however, the limited number of RSUs along interstates or primary roadways may limit assessment to a much smaller number of locations. Requirements for storing additional "snapshots" of data would require modification of the standard OBE, and/or the addition of flash memory by an OEM. Historically, OEMs have resisted attempts to increase the price of vehicle components without a corresponding increase in value for either the customer or for marketing purposes. As such, asking or requiring OEMs to increase memory storage for data collection purposes is a difficult proposition.

In addition to limitations imposed by J2735, the required VDOT sample interval of 6 inches requires high sampling rates and creates large files, which in turn increases the difficulty of data transmission. VDOT currently records IRI in $1/10^{th}$ mile increments for contractor-provided data; the 6 inch sampling interval is greater resolution than required to produce this level of detail. According to Raja Shekharan in a personal interview on June 20^{th} 2011, there are no references or technical documents to support the requirement; it is a convention likely derived from VDOT contractor capabilities. The connected vehicle program was not intended to support intense data collection efforts; in its current form it will not support IRI collection to VDOT standards, and thus any gathered data would be a roughness estimation.

Data Transmission

Using DSRC to transmit required pavement assessment data from vehicles to infrastructure is difficult due to the large amount of data required for pavement assessment. In a 2011, Auburn University used two Kapsch Multi-Configurable Networking Units (MCNUs) and DSRC radios to determine expected data transfer speed from the V2I system. Unprocessed accelerometer data generated from 2,700 meters of test track (a file size of about 2mb) took more than 20 seconds to transfer between stationary communications units [3].

In a 2011 experiment, Auburn University field tested the effective range of DRSC radios by driving a test vehicle equipped with DSRC away from a stationary DSRC unit until packets of data were lost while transferring a large file. Researchers determined the effective range (without data loss) of the DSRC radios to be approximately 700 meters in line of sight conditions, contrary to the 1,000 meter advertised range. At freeway speeds of 70 miles per hour (31 m/s), vehicles will travel approximately 620 meters during a 20 second data transfer, not counting acquisition time or restarting due to errors [3]. Combined with operational reductions in data transmission quality due to environmental factors, reliability may suffer.

Data loads could be reduced through pre-processing vertical accelerometer data and conversion to IRI by a vehicle OBE. Pre-processing would enable the vehicle to transmit only the final or near-final estimate, and not the intermediate vertical accelerometer readings necessary for conversion. Transmitting post-processed data could reduce data loads; VDOT uses average IRI over a $1/10^{th}$ mile increment, which is represented by three numbers; left wheelpath IRI, right wheelpath IRI, and average IRI.

4.1.2 System Requirements

The connected vehicle approach is intended to capture data output from privately operated vehicles operated on public roadways. The system requires roughness information to be collected on the roadway network every two weeks to one month, and thus will require a base technology penetration rate to prove effective. The system uses technology which has not yet been implemented; however, a recent analysis by Auburn University researchers indicate a market penetration of less than 2% would be sufficient to provide daily roughness updates [3].

Variations in accelerometer specifications as installed in modern vehicles, coupled with varied driving styles, vehicle loading, and vehicle changes made by the consumer (i.e. replacing the wheels and tires) mean relatively low control over the type of frequency input, and thus the resulting data quality. Accelerometers in stock vehicles may be calibrated prior to leaving the factory, or a central processing station can apply pre-calibrated algorithms. However, over time the vehicle configuration may change due to wear, changes in loading, etc., which can decrease the accuracy of the roughness estimation over time.

The objective of reliable transmission of roughness information to a central database is not met utilizing this approach. The amount of data required to meet the current roughness assessment standards required by VDOT creates difficulties in storage and transmission of data using DSRC. The SAE J2735 communications standard places limitations on data transmission and capture, and a small number of RSUs, particularly at early phases of adoption, will degrade the ability of vehicle OBEs to offload information at a sufficient rate to support roughness assessment.

4.1.3 Installation/Integration

The connected vehicles program, once implemented, will serve as a basis for many types of data gathering applications. This paper initially investigated the pavement assessment application as an add-on to the connected vehicle program; however, in the course of investigation it was determined to be difficult without modification to the J2735 standard or individual vehicles. Reprogramming the OBU and adding additional flash storage may allow some roughness estimation capability; however, the data transmission issue may still require significant work to solve, or require an alternative approach.

Private owners, dealership networks, and vehicle manufacturers currently have no incentive to allow vehicles to be modified, and there is limited means to ensure placement of modified vehicles to ensure maximum coverage. Potential solutions include modification agreements with vehicle manufacturers or dealerships on a case-by-case basis and the installation of modifications as vehicles arrive for servicing; however, this does not mitigate use vehicle modification and data quality concerns.

4.1.4 Cost

The cost of the connected vehicles approach is difficult to quantify, as it involves infrastructure and vehicle systems which have not yet been implemented. Ignoring the cost of implementing the connected vehicle program, this approach should prove relatively inexpensive when compared with other, more equipment-intensive approaches. Modification of the vehicle OBU with additional memory and processing unit, assuming an 8GB increase in memory capacity and an Intel i3 mobile computing processor, should be less than $200 per vehicle. There are fixed infrastructure costs associated with the storage and processing of information transmitted by these vehicles, particularly if unprocessed vertical accelerometer data is transmitted to a central server. Assuming a $20,000 server cost and the ability of the server to support 100 vehicles, a 100 vehicle system would cost approximately $40,000.

4.2 Fleet Vehicle Approach

The fleet vehicle approach uses semi-permanent, aftermarket accelerometers installed in department or state-owned vehicles, rather than vehicles operated by the public. Aftermarket accelerometers are connected with GPS units for positional information and wireless communications devices for data transmission. The fleet vehicle approach can be visualized as shown below in Figure 4.2.1

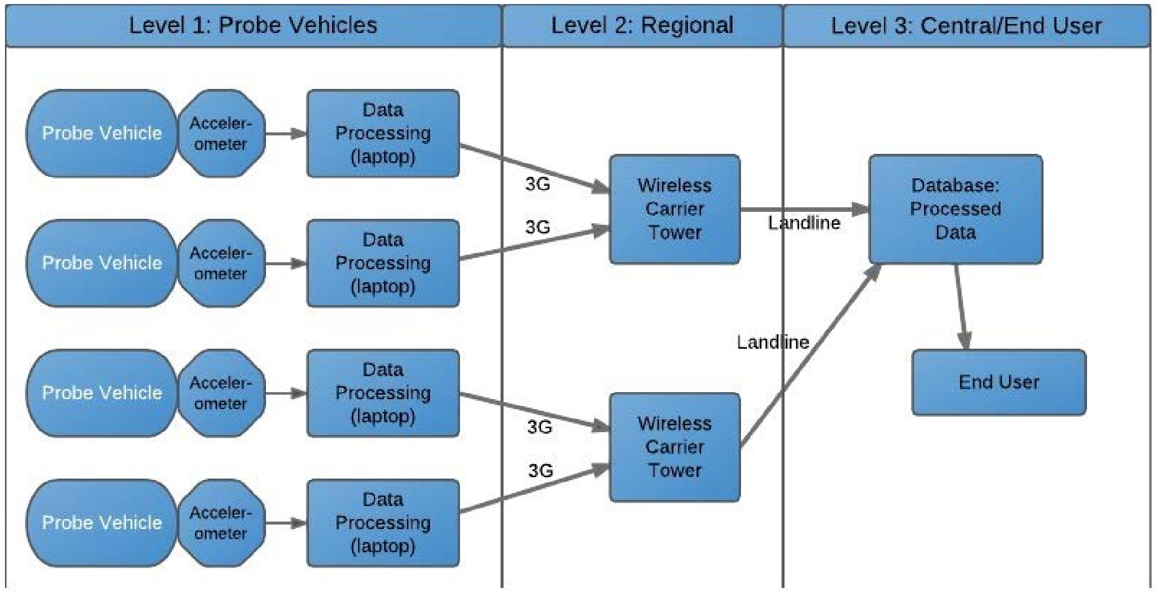

Figure 4.2.1: System Diagram of the Fleet Vehicle Approach

4.2.1 Technical Analysis

Analysis of the technical aspects of the fleet vehicle approach yield interesting results. High-quality aftermarket accelerometers allow the governing body to pick the specifications without relying on public vehicles and their limited information, and the required vehicle installations and calibrations allow accuracy not feasible with other approaches. Finally, data transmission using a wireless network increases the signal coverage and reliability necessary to provide usable data.

Accelerometers

The fleet vehicle approach is exemplified by research at Auburn University as described in Chapter 2. Auburn research has produced usable roughness data from aftermarket accelerometers, and is currently attempting to capture IRI or a near-equivalent from accelerometers. The 6-axis accelerometer used in the Auburn test vehicle is located at or near the vehicles center of gravity (CG), and is mounted in such a way as to accurately capture pitch, roll, and yaw rates, in addition to vibrations transmitted through the chassis. The accelerometer used in tests is a Crossbow IMU 440, which captures angular rates (roll, pitch, and yaw) and linear accelerations. The accelerometer has a range of +/- 4gs, and resolution, accuracy, and temperature ranges which compare favorably with automotive-grade accelerometers.

The approach has been proven effective in a research setting, and is translatable to larger-scale testing and implementation [3]. However, the accelerometers and equipment necessary to provide position information (GPS units) and data storage (currently a laptop) drive up the unit cost. The accelerometer runs at a high sampling rate, producing large quantities of data. Large data loads may prove troublesome and costly for data storage and transmission systems.

Data Transmission

Data transmission for the fleet vehicle approach is similar to the system outlined for both the mobile device approach and the connected vehicle approach, with the exception of the ability of the vehicle OBE to pre-process data for simpler transmission. Options include DSRC radios interfacing with RSUs or units installed in vehicle parking garages etc., local wireless networks, or a commercially available data transmission services from a mainstream wireless carrier (i.e. Verizon). DSRC radios carry significant drawbacks for data transmission to RSUs, such as high installation costs and limited range. The limited number of RSUs and home-based DSRC radios limit the real-time nature of captured data by operating only when a vehicle is within range of an RSU.

Other transmission options include use of an existing wireless network; this is the preferred option. This approach requires connection to the Linux-based operating system and laptop required to drive the accelerometer and capture the associated data stream. Advantages of using wireless include the “ready now” timeline for use, nationwide coverage, and fixed-cost package for data transfer outsourced to another entity for maintenance and upgrades. Separating the roughness data stream from safety-related V2I communications prevents overloading of the DSRC system. Downsides include the fixed monthly cost and limited upload and download speeds, and potential interruptions from transitions from cell tower to cell tower.

The availability of computing power in the form of a laptop computer within the installed equipment package in each vehicle means the ability to pre-processing data to reduce file size prior to transmission. Pre-processing eliminates the need for post-processing at a central location, potentially saving server costs and computing time. Smaller file sizes may also increase transmission system reliability. A customized, dedicated sensor package installed within the vehicle may replace a laptop for data processing, reducing costs.

4.2.2 System Requirements

Few probe vehicles are employed using this approach relative to the connected vehicle approach, which could prove troublesome when attempting to provide coverage for an entire roadway network. Coverage will require installation in vehicles which travel great distances on a daily basis in support of other activities, such as US Department of Agriculture inspectors, DOT inspectors, or other agency-operated vehicles. Individual installations and calibrations allow for increased control of data quality, and ensure the vehicle is not modified without the DOT's knowledge.

The use of a commercial wireless carrier to transmit data to a central database allows this approach to transmit data to a central database for near-real time interpretation. However, the size and composition of the fleet presents a challenge for meeting the daily coverage requirement. Virginia's highway system contains approximately 57,867 miles of roadway; with a fleet size of 50 vehicles, each vehicle would have to drive over 1,000 miles a day to provide coverage. Using a update scheduled of every two weeks, each of the 50 vehicles would have to drive about 120 miles a day to provide full coverage. If the vehicles are not driven specifically to cover the entire roadway network, as will certainly be the case, semi-weekly coverage will drop dramatically. This is a significant drawback associated with the fleet vehicle approach, as it does not meet the system requirements as originally outlined.

4.2.3 Installation/Integration

In order to capture an accurate picture of roadway roughness and ensure consistency across various vehicle platforms, accelerometers must be mounted in a location which transmits vibrations from the vehicle chassis with a minimum of interference. Interior coatings, materials, and upholstery can dampen and deaden vibrations coming from the roadway through vehicle suspension, tires, and chassis. In Auburn's research, vehicle IRI was found to be correlated with vertical accelerations along with pitch and roll; thus a central mounting location is critical for installation.

The fleet vehicle approach requires significant resources and effort to install in each vehicle, and as such is only suited for installation in government-owned vehicles. The installation includes a permanent accelerometer mount within the armrest of the vehicle, and is not easily transferrable from one vehicle to another. The DRSC radio, IMU, and laptop require mounting equipment and take up space; this may change the ability of the vehicles to complete other missions, restrict the number of passengers, or require special equipment (i.e. an AC/DC converter to run the laptop) to be installed. Auburn researchers used an Infinity G35 sedan; utility vehicles which comprise the majority of many state DOT fleets may require further modification or calibration. State-owned fleets are generally comprised of vehicles with similar specifications, and thus only one or two vehicles may need to be calibrated.

4.2.4 Cost

The most easily quantified measure of cost is capital associated with purchase of equipment, labor and installation costs, and ongoing or recurring costs based on equipment maintenance, data plans, or other factors. The equipment costs associated with the two approaches are much different. The fleet vehicle approach requires several components linked to a central, Linux-based laptop, including a Crossbow 440 Inertial Measurement Unit (IMU), a Novatel Propak-v3 GPS receiver, and a Kapsch MCNU.

Figure 4.2.4.1: Crossbow 440 IMU [37]

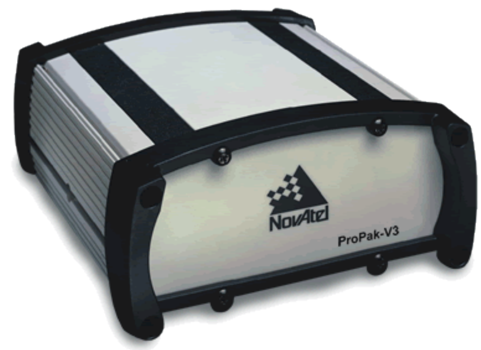

Figure 4.2.4.2: ProPak-v3 [38]

According to Auburn researcher Jeremy Dawkins in a personal interview on June 15, 2011, the combined cost of components including the laptop and DSRC radios is approximately $7,000. These systems could likely be combined into a relatively low-cost instrument package, eliminating the need for a complete laptop and expensive IMU. Transmission capability may be provided by either DSRC radios or using WiFi to transmit data while the vehicle is in the shop area. Development costs may vary according to whether it is developed internally or by a consultant; this paper assumes the instrument package will cost approximately $400 per unit.

There are fixed infrastructure costs associated with the storage and processing of information transmitted by these vehicles, whether by Wifi or by DSRC, and these costs become more significant if unprocessed vertical accelerometer data is transmitted to a central server. Excluding the cost of WiFi and/or DSRC receivers and assuming a $20,000 server cost with the ability to support 100 vehicles per server, the unprocessed data transmission option costs for a 200 vehicle system would be $140,000. However, if vehicle instrument packages were capable of pre-processing and interpreting data, server costs could be largely eliminated. For example, if the instrument packages cost $600 per vehicle and eliminated the server costs, the system becomes completely scalable outside the fixed costs of DSRC or WiFi receiver infrastructure, and costs will dependent upon the number of vehicle units installed, i.e. a 50 vehicle fleet would cost $30,000, and a 100 vehicle fleet would cost $60,000.

4.3 Mobile Device Approach

One option for gathering pavement roughness data on a large scale in the near future is use of the accelerometers installed in many modern mobile communications devices to capture roughness data. Modern smartphones such as the Droid and iPhone are equipped with 3- or 6-axis accelerometers which are used for a variety of applications within the phone’s operating system. As outlined in the literature review, these accelerometers are sensitive enough to capture road roughness data as transmitted through vehicle suspension, tires, and a mounting bracket. In general, the positive aspects of this approach include ease of installation, low cost, relatively large market for data gathering if released to the general public, and flexibility to be used with multiple agency-owned vehicles with a minimum of installation effort. Downsides include limited usefulness of generated data (due to limited correlation with existing pavement roughness indicators) and increased chance of operator error or vehicle modification issues if the operational plan includes public dissemination of the application. A system diagram of the mobile device approach is shown in Figure 4.3.1 below.

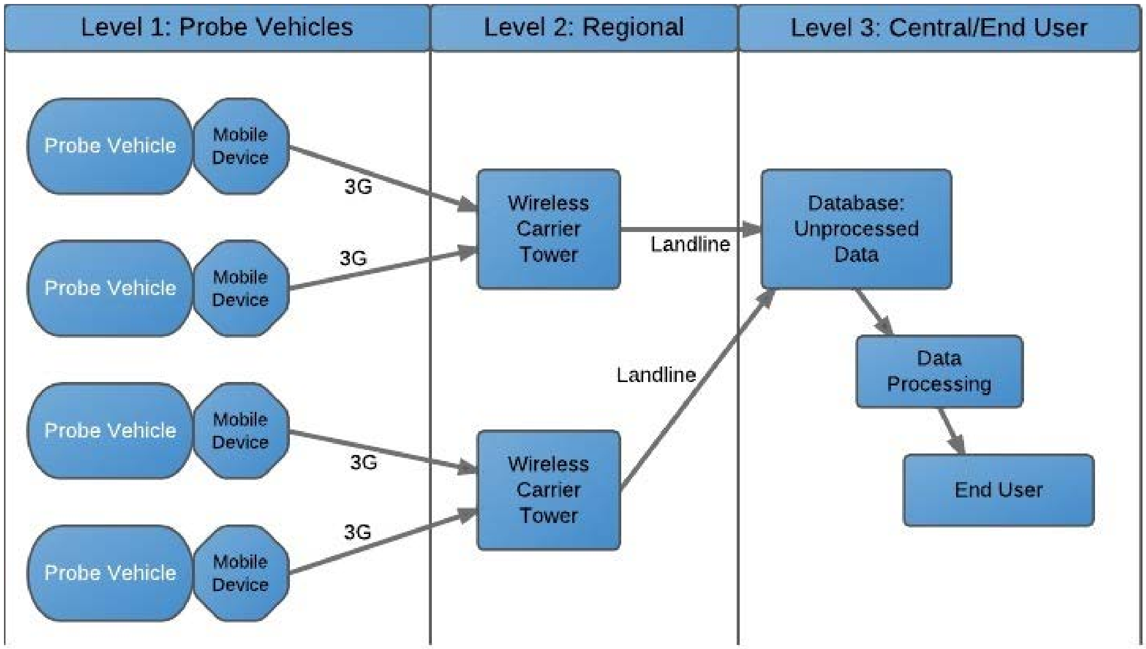

Figure 4.3.1: System Diagram of the Mobile Device Approach

4.3.1 Technical Analysis

Technical analysis of the smartphone approach yields several general conclusions regarding the feasibility of capturing roughness data using smartphones. First, the specifications for smartphone accelerometers are similar to those of OEM-equipped vehicles. Exposed to similar inputs and with additional research on mounting techniques, smartphone accelerometers should achieve similar results to those outlined in Auburn experiments. Second, the data quality is, in general, less suitable for measures of road roughness than using vehicle-integrated or dedicated accelerometer data when used with a commercially available vehicle mount. Lastly, the approach can be implemented on a large scale due to the market penetration of mobile devices, but incentives for private citizens to participate must be carefully designed to encourage participation.

Accelerometers

Ralph Robinson, a researcher at UMTRI, has developed an Android operating system-based application which utilizes the internal accelerometers of a Motorola Droid smartphone to capture pavement roughness and transmit the information to a central database. The application also utilizes Bluetooth to capture information from the vehicle's OBD port and Bluetooth-enabled sensors. Initially the application sampled accelerometer output at approximately 500 Hz, or 500 samples per second. However, this high sampling rate proved too rapid for either the accelerometer used by the Droid device or the Android 2.2 operating system. As such, the sampling rate was modified to 100 Hz, which provides a sampling interval of approximately 10.5 inches at a vehicle speed of 60mph.

The Droid phone uses accelerometers sourced from ST Electronics, model LIS331DLH. These accelerometers have relatively low power draw (down to approximately 10 uA), and the g-force range can by dynamically selected based on user input, including +/-2g, +/- 4g, or +/-8g. Compare this with the +/-1.5g of vehicle ABS sensors, and the +/- 6g of rollover protection sensors, and the +1.5 to -3.4g with acceleration reported to the nearest 0.02g reporting requirements/limits outlined in J2735. Data output rates for the LIS331DLH are between 0.5 Hz and 1 kHz, or once per second up to approximately 1,000 times per second. The sensors have a sensitivity of between 0.001 and 0.0039 g depending upon the measurement range setting; this is adequate for the purposes of roughness measurement [38].

The ST electronics accelerometer is representative of the type of device which can be found in an average smartphone manufactured over the past several years (2009-

2011). In a review of similar smartphones (iPhone 4, LG Optimus 3D, Droid Incredible 2, and Nokia N900), models equipped with accelerometers had similar characteristics, such as selectable g force ranges between 2g and 8g and similar temperature ranges. Sensitivity ranged from the above-mentioned 0.039g up to 0.072g, and the sampling rate was capped at 400 Hz for other accelerometers [39, 40]. More specific research is needed to completely eliminate sub-standard accelerometers employed for older-generation smartphones, but overall the similarity of specifications means a pool of similarly equipped smartphones are available, greatly simplifying the task of identifying and disregarding erroneous or inadequate data.

As of the date of this writing, UMTRI was still several months removed from publishing studies on data quality, but based on preliminary findings the roughness data gathered will be difficult to correlate with existing pavement assessment indices such as IRI. UMTRI is instead attempting to correlate the data gathered by smartphone accelerometers within the existing 10-point PASER scale currently used by personnel conducting windshield surveys to rate the condition of pavements in Michigan. According to Ralph Robinson of UMTRI, the lack of similarity between vehicles, mounting locations, and potentially weather patterns may mean analysis of larger datasets captured over multiple runs rather than absolute roughness captured by the accelerometers may be necessary to utilize roughness data captured by smartphones.

Data Capture & Transmission

One way to emulate the greater control and higher data quality of the fleet vehicle approach without the high cost would be to mount smartphones in a fleet of vehicles in a manner similar to the dedicated accelerometer. This would require assessing multiple mounting locations within each vehicle and selecting one which would most accurately transmit vibrations, pitch, and roll. According to Ralph Robinson of UMTRI in a personal interview on June 3, 2010, this usually means mounting to the frame of the vehicle; windshield mounting is not acceptable.

The mobile device approach holds a decided advantage over separate communications and data-gathering hardware used in the fleet vehicle approach, as mobile devices are integrated with wireless data service. Mobile devices and wireless carriers also support data transmission (upload) rates of 0.5 megabytes per second and up. As a means of comparison, a test track of 2,700 meters (1.7 miles) generates approximately 2 megabytes of data and requires approximately 100 seconds to complete at 60 mph. Thus, the data transmission rate of commercial wireless is more than sufficient to transfer roughness information in support of near real-time data updates.

4.3.2 System Requirements

The smartphone approach, if widely and voluntarily implemented by private users, can potentially provide the type of whole-network coverage required for this system. According to Auburn research, a less than 2% market penetration rate (for drivers) is necessary for pavement condition updates on a two-week schedule. The U.S. smartphone market penetration rate is forecast to be 50% by August 2012, with well over 100 million units in use [41]. If 0.1% of smartphone users are equipped with this application, 100,000 data-gathering devices will be driven on roads in the United States daily, with a small fraction of those in Virginia; this should provide coverage on the majority of roadways every two weeks.

The second requirement is transmission back to a central server or database. The sheer volume of data potentially generated by this approach is comparable to that generated by the connected vehicle approach. A larger server system, combined with significant processing power, would be required to aggregate, store, and process incoming information. Unlike with the J2735 approach, there is no system in place to assist with data transmission duties, and thus a server system and infrastructure would need to be constructed and tested.

4.3.3 Installation/Integration

There are two installation options for the smartphone approach; permanent and non-permanent. Non-permanent installation involves a windshield mount and a power supply. According to Ralph Robinson of UMTRI, installation which produces the best results calls for mounting the smartphone in a windshield mount and lowering the phone and mount combination until it contacts the dashboard and/or instrument panel. This setup allows the vibrations from the vehicle to be transmitted through to the smartphone and be captured by the internal accelerometers, and prevents the phone from changing orientation during operation. Permanent installation is more involved, with alterations to the vehicle's interior necessary to allow more direct transmission of vibrations.

One distribution option is installing smartphone systems and mounts to vehicles in the VDOT motor pool. Installation in pool vehicles will make efficient use of current resources, allow constituency in installation, and allow for limited control of driver routes in the event a section of road requires attention. A second, perhaps more difficult distribution option is to promote the application to the general public through smartphone application stores, provide the necessary mount and/or hardware, and give instructions for use. Challenges associated with this distribution method include the lack of incentive for public users to participate, the possibility of incorrect installation, and limited interaction with vehicle drivers. Wireless carriers charge for data use; users may be reluctant to use bandwidth on a *pro bono* basis. Incentives such as a reduction in vehicle registration fees or taxes may prove effective if participation is tracked accordingly.

Another barrier to private use is resistance to the idea of tracking individual road users by government or non-government authorities, as evidenced by several court cases and recent events. The recent disclosure that a popular smartphone operating system captures and allows access to individual position information created backlash against the company in the form of a lawsuit [42]. Smartphone tracking and privacy issues were also the topic of a recent Senate hearing [43]. Software can be developed to ensure the anonymous nature of data gathering for the purposes of data aggregation, but sensitivity to privacy issues remain.

4.3.4 Cost

Costs associated with this system vary widely based on the number of eventual users, and if private users will use the application developed without the Bluetooth-enabled OBD II port device, which drives up cost. For installation by a department of transportation, the cost of components for the smartphone system includes the cost of the Droid phone itself ($200 with a 2-year contract on Verizon), the monthly voice and data contract (~$90), plus a small, Bluetooth-enabled device which connects to the vehicle's OBD II port to transmit speed, which are available on the market for approximately $100. There are several optional sensors associated with the smartphone approach, which include ambient temperature, pavement temperature, and several others. These other sensors are not required for the base capability of pavement roughness assessment, but may supply additional information to decision-makers on an as-needed basis.

Costs for this system are spread out over a greater period of time than the other two options, as the monthly data contracts cover a significant portion of the total cost of the phone and transmission capabilities. For example, the cost of the Droid is approximately $200, but monthly charges are up to $90 including taxes and fees; a data-only option may be available for $30/month. Assuming, as with the fleet vehicle approach, that the smartphones can pre-process data using an application, capital costs would be completely scalable to the number of probe vehicles. Each vehicle would require an Android-capable phone ($200), a windshield mount ($50), and a Bluetooth-capable OBD II device ($100) for a capital cost of $350 per vehicle. Assuming data plans for each vehicle at $30/month, this would mean the first year cost for each vehicle would be 12 x $30 = $360, plus the capital cost of $350, for a total of $710; a fleet of 50 vehicles would cost approximately $35,500.

4.4 Data Volume Challenges

The pavement roughness data gathering systems outlined in this paper all share one element; generation of large amounts of data on a recurring basis. The storage, use, and aggregation of pavement roughness data is an important consideration in system design. A case study is presented below using the volume of data generated by the Auburn experiments (1.2mb/vehicle/mile) and the 2009 AADT values for 3 major roads (US 250, US 29, and SR 20) in the Charlottesville area, obtained from the VDOT Traffic Counts program [44]. The road segments have AADT values which range from 5,400 to 51,000 with a median of 14,500, and cover 14.3 miles of roadway. Roadway segments are displayed on the map below. Assuming a 100% market penetration for data gathering equipment and probe vehicles, 370 gigabytes of roughness data will be produced on a statistically average day. The 100% market penetration for probe vehicles is far removed from the present state; however, even a 1% market penetration provides 3.7 gigabytes worth of data per day for less than 15 miles of roadway in Charlottesville. The roadways used in this case study are displayed in Figure 4.4.1 below.

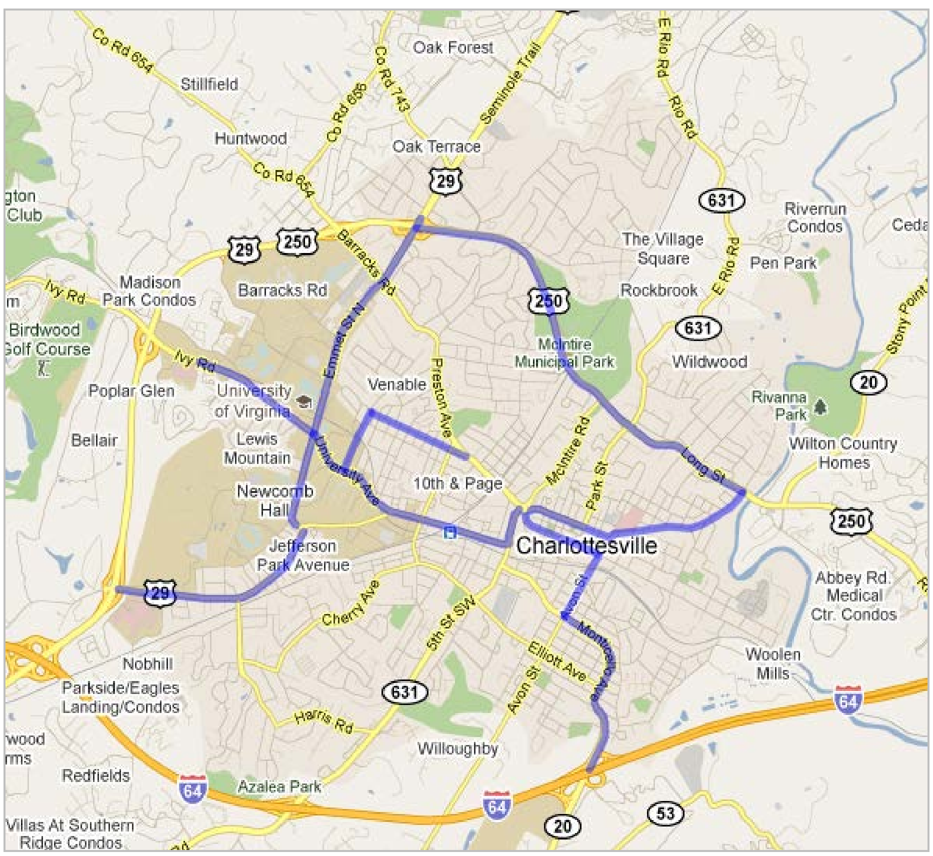

Figure 4.4.1: Case Study Roadways in Charlottesville

The sheer volume of data captured after even a small market penetration presents a challenge of its own. This case study covers less than 15 miles of roadway; Virginia has a highway network of nearly 58,000 miles. Charlottesville covers 10.3 square miles, with a population of 43,000 during a 2010 census. In contrast, the District of Columbia covers 61.4 square miles with a population of 600,000 people. Clearly, some type of filter or selective data gathering system will be required concurrent with any large-scale implementation of a pavement data-gathering program.

As stated previously in this paper, pavement roughness information updated every two weeks to one month is likely the practical minimum interval during which potential changes in pavement roughness for pavement maintenance decision-making purposes may be observed. Aggregating the readings sent back from multiple vehicles to create a statistically significant and/or accurate roughness reading useable by VDOT. Data gathered from a small subset of vehicles traveling the roadway will be adequate for the purposes of updating roughness measurements bimonthly, although the exact number of passes required for a reliable accurate update is unknown. It may be useful to capture roughness readings daily for the purposes of updating the "Dashboard" function on the VDOT website, or to provide information for high-priority maintenance (potholes, etc.).

4.5 Cost

The economic benefits of aggregated pavement roughness data are in the form of value to the governing entity minus the cost of equipment, training, data storage, and ongoing labor expenses. There are three general categories which should be considered when analyzing the total cost/benefit of the proposed pavement maintenance data-gathering systems. First, the labor and materials consumed by existing alternative data-gathering approaches, if they exist. In the case of the Michigan Department of Transportation, the roughness data gathered by the smartphone approach is intended to replace a windshield survey currently conducted by MDOT employees. In the case of VDOT, a contractor is employed to gather roughness data at an annual cost of $1.8 million. The second category is the anticipated cost savings to the governing agency through application of the pavement assessment data combined with revised maintenance techniques, above and beyond the direct cost savings realized by the replacement of an alternative approach. For example, the ability to apply maintenance to a stretch of roadway instead of replacement or re-milling potentially saves DOTs maintenance costs when compared with the baseline case of not employing the system.

The contractor tasked with collecting roadway data currently gathers IRI along with NDR, LDR, and videos of other infrastructure such as road signs and guard rails. It is unlikely roughness data will replace the suite of sensors employed by contractors in the near future, as VDOT pavement maintenance decision matrices depend upon the gathering of these specific indices and distress quantities. Any change in pavement decision-making would require a systematic change in the way pavement decisions are made, and the value of these changes is difficult to quantify without additional research.

In order to restrict spending and use monetary and developmental resources on only necessary system capabilities and efforts, a Concept of Operations has been developed as part of this paper; it is included in Section 5 below.

Chapter 5: Concept of Operations

This chapter provides a formal concept of operations for the proposed probe vehicle-based pavement roughness estimation system. The purpose of a concept of operations (ConOps) is to describe the scope, operational needs, support environments, and operational scenarios of the system from a user perspective. In this case, the user is a department of transportation or entity responsible for the maintenance of a roadway network. The system described in the ConOps uses privately or government-owned vehicles (probe vehicles) equipped with accelerometers to measure vertical acceleration for the purpose of collecting pavement roughness data, transforming the data into useable indicators of pavement condition, and transmitting the data back to a central database for interpretation and use. Included in this ConOps are the scope, parameters, and constraints of the proposed system [45].

This ConOps incorporates several separate sources of information. First, the capabilities of vertical accelerometers as outlined by the University of Auburn in their final report on the use of accelerometers to estimate road roughness [3]. Second, the capabilities of connected vehicles within the ITS program utilizing the J2735 standard messaging set as outlined by SAE. Lastly, the ConOps was based on gaps in VDOT's road roughness information, such as timely roughness information on secondary roadways, and on lanes other than the right-most lane, which is currently the only lane covered by the VDOT contractor.

5.1 Scope

This section presents an overview of the Concept of Operations, including the following elements:

- Document Purpose and Outline
- Purpose for Implementing the System
- Objectives and Goals
- Involved Agencies
- Identification of Intended Audience
- Scope of the System

5.1.1 Document Purpose

The purpose of this ConOps document is to describe the and outline a system which uses probe vehicles to collect pavement roughness data using internal accelerometers, transform the data into useable indicators of pavement wear, and transmit the data back to a central database for use by a governing body or state department of transportation. The document is intended to outline basic system components, give a detailed outline of the purpose of the system, and provide stakeholders with information for decision-making on the costs and benefits of the proposed system.

This concept of operations document is organized as follows:

- **5.1 Background**
- **5.2 User-Oriented Operational Description**
- **5.3 Operational Needs**
- **5.4 System Overview**
- **5.5 Operational and Support Environments**
- **5.6 Operational Scenarios**

5.1.2 Background

Pavement condition data on interstates, primary roads, and secondary roads in the state of Virginia is currently collected by a VDOT contractor. The contractor (Fugro/Roadware) uses specialized vans equipped with multiple sensor systems, including lasers, accelerometers, cameras, and lights to gather pavement condition data. After collection, a computer program analyzes captured data and images and provides detailed distress data and pavement roughness information, including IRI, to the Virginia Department of Transportation (VDOT)'s staff.

This ConOps outlines a proposed system based on the principles of the government's Intelligent Transportation Systems (ITS) initiative which uses accelerometers based in probe vehicles and wireless communications devices to replace or supplement the existing contractor-based system. The ITS initiative aims to introduce intelligent vehicles, infrastructure, and communications systems to the nation's transportation system. The core of the ITS program is the connected vehicles research program, which aims to wirelessly connect vehicles, infrastructure, and mobile devices to improve safety and efficiency.

Connected vehicle technology and concepts are potentially adaptable to data-gathering roles, including collecting pavement roughness data for use with pavement maintenance and asset management programs. Recent research shows the potential for accelerometers either installed in vehicles or contained in mobile communications devices to gather pavement roughness data [3]. A pavement roughness data gathering system consisting of a fleet of accelerometer-equipped and communications-enabled vehicles can supplement contractor-operated data collection vehicles. Multiple system configurations are possible as outlined below.

1. Use the ability of future connected vehicles to utilize internal sensors and transmit data via wireless communications, whether it is rollover protection sensors or sensors contained in smartphones.
2. Install accelerometer, data transmission, and processor packages in a smaller number of government or stakeholder-owned vehicles, which would allow for more advanced quality control and governance over gathered data.
3. Use mobile communications devices such as smartphones to gather roughness data and transmit over wireless networks.

5.1.3 System Purpose & Justification

The pavement roughness data gathering system, as part of or separate from the US Department of Transportation (USDOT)'s Intelligent Transportation Systems (ITS) initiative, will be used to gather pavement roughness information for the purpose of increasing information available to pavement maintenance decision makers in Virginia. This application will increase the frequency of collection of pavement condition data for primary and secondary roads, interstates, expand the network of monitored roadways, decrease lag time from data collection to useable information, and add to the total amount of information available to state transportation agency employees for the purposes of roadway maintenance.

Using probe vehicles to gather data offers several advantages over the current, single-source data collection system. First, it allows more frequent updates of roughness data and coverage for an increased number of lane-miles on an annual basis. Second, such a system could lower data gathering costs by either decreasing the frequency of VDOT contractor data collection or allowing tightly focused assessments when warranted, as opposed to blanket coverage. Third, it will help move probe-vehicle applications and research forward by proving that such applications are feasible in full-scale, real-world applications. Lastly, such a system could allow for more sophisticated and accurate pavement deterioration tracking, as current methods depend on the use of pavement deterioration models to predict pavement condition between assessments [3].

Although Virginia interstate highways and primary roads are covered each year by pavement assessment vehicles, highly trafficked secondary roads and other connectors are covered at a lower frequency. Some roadways may be completely outside of coverage, including rural roadways, suburban streets, and other areas which are a low priority for funding. Some roadways may be the responsibility of a city instead of the state; in this case, information could be shared with local governments. Increasing the frequency of data collection or expanding the total coverage of roughness collection by VDOT contractors using conventional methods would increase total cost of roadway maintenance decision-making and create a recurring expense for Virginia taxpayers. In the current climate of budget-cutting and fiscal overruns, increasing budgets for specific programs is politically difficult, and allowing decision makers to collect data at a lower cost than current methods represents a substantial step forward.

Reducing the cost of pavement assessments is another goal of implementing a probe-vehicle based roughness collection system. Currently, Fugro collection vehicles cover roadways on a fixed schedule, irrespective need or the pavement's position in a typical pavement life-cycle. For example, pavement will be rehabilitated in Northern Virginia on a section of Interstate 66 near Route 50 beginning in April 2011 and ending in March 2012 [46]. A Fugro van passing through this area within a few months of completion is not necessary, as the stretch of roadway is clearly not due for maintenance for several years. Fewer, more targeted runs on potential trouble spots identified by a network of probe vehicles gathering roughness data should prove more cost effective than blanket coverage. Decreased costs would stem from reducing the number of total runs necessary and reducing data processing, storage, and presentation costs.

In addition to tangible, application-specific advantages of a probe vehicle data-gathering system, implementing a probe-vehicle based pavement assessment will show the value of ITS outside of safety. The market penetration of smartphone technology and vehicles equipped with DSRC and OBEs is increasing, and these technologies are potential data-gathering devices for maintenance agencies. Accelerometers, GPS devices, light sensors, magnetic heading indicators, and other sensors are standard equipment on many smartphones and vehicles, and quantity of sensors should only increase as the mobile technology and automotive industries continue to innovate.

Perhaps the most compelling argument for implementation of probe vehicle-based pavement assessment systems is the ability to detect and target areas of pavement which have reached a specific inflection point in the degradation curve. Pavements tend to degrade in a similar manner over time, as shown in Figure 5.1.3.1. Roughness can be an indicator of where pavement currently is along the degradation curve, and is a factor in some state DOT's overall pavement condition indicators. Increasing IRI values can serve as a trigger for more detailed analysis of specific sections of pavement, or as a standalone indicator of pavement condition. For example, the New York State Department of Transportation (NYDOT)'s condition indicator, known as the Pavement Condition Index (PCI), is a composite index, of which 35% is attributable to IRI [31].

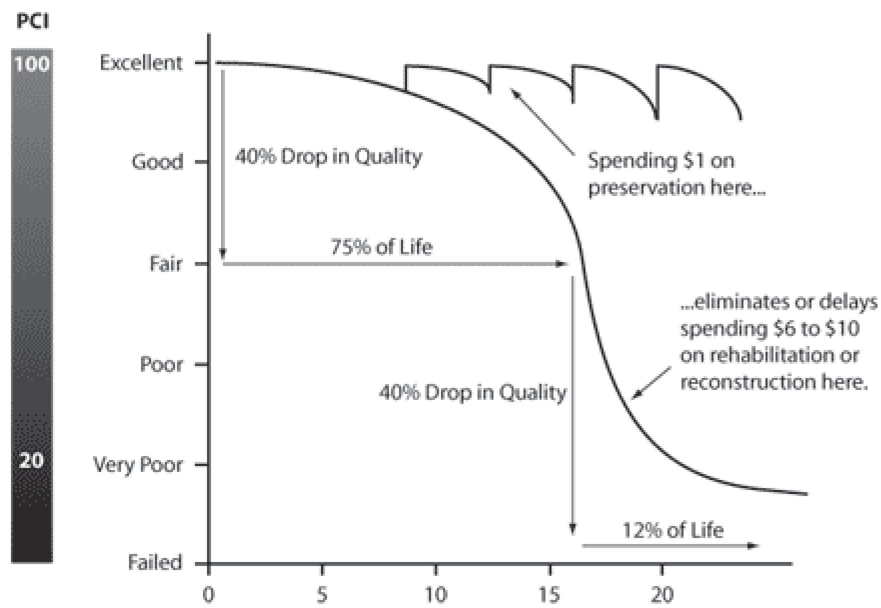

Figure 5.1.3.1: Typical Pavement Deterioration Curve [47]

5.1.4 Objectives and Goals

Objectives of the pavement roughness data-gathering system are as follows:

1) **Produce Usable Data.** Utilize probe vehicles to collect pavement roughness data on a statewide roadway network, including interstates, primary,

secondary, and neighborhood roads, with sufficient frequency to provide bimonthly updates on pavement condition.

2) **Transmit to Database.** Transmit the roughness data to a central database for transformation into a meaningful measure of roadway condition, such as IRI or equivalent indicator.

3) **Integrate with Existing Pavement Maintenance Decision Systems.** Data produced by the data gathering system should be usable within the current VDOT decision-making system, such as an estimation of IRI.

The goal of the system is to provide more frequent coverage for an increased number of lane-miles when compared with current methods, intended to supplement current condition assessment methods. The roughness assessments should lead to improvements in pavement maintenance decision making, decreased dangerous pavement condition maintenance response time, and increased safety and lower costs for the public.

5.1.5 Involved Agencies

The primary beneficiary agency will be the Virginia Department of Transportation (VDOT). Supporting agencies include USDOT, the Federal Highway Administration (FHWA), and other federal transportation authorities. If insufficient road network coverage is provided by VDOT, USDOT, or FHWA vehicles, other agencies which operate fleet vehicles such as the US Department of Agriculture (USDA), may act as probe vehicle providers. Automobile manufacturers, standards organizations such as ASTM, SAE, and some research institutions may also be involved.

5.1.6 Intended Audience

This document outlines the vision of the pavement assessment application to the planners and stakeholders involved in data-gathering and roadway maintenance decision-making operations, as well as researchers directly involved in adopting smartphone or DSRC communications technology to gather probe data using private or publicly owned fleet vehicles.

5.1.7 Scope of the System

The pavement roughness data gathering application discussed in this document is limited to the following capabilities and systems:

1. Gathering data from vehicle sensors, including but not limited to vertical, lateral, and longitudinal acceleration, yaw, pitch, and roll for the purpose of analysis in the context of pavement applications, and the compilation of this data in a vehicle on board equipment computer or other on-board memory storage device.
2. Transmission of data via vehicle-to-infrastructure (V2I) wireless technology to roadside units (RSUs), or by an existing wireless communications network.
3. Compilation of data into a usable form (IRI or other pavement roughness indicator), and dissemination to appropriate stakeholders. The compilation of data will include quality control measures such as a minimum number of passes from properly-equipped vehicles prior to the use of data for maintenance applications, the proper data format, and the type of database used for presentation and access by the appropriate authorities.

4. Addressing privacy and information security concerns by isolating collected data, how the data is used, and identifying measures to ensure that data is not tied to individual user location, personal information, or other privacy-sensitive data.

5.2 User-Oriented Operational Description

This section will describe the system from a user's vantage point. The section will identify how organization and system-specific goals and objectives are accomplished, including strategies, tactics, policies, and constraints. Information highlighted in this section includes stakeholders, stakeholder and user activities, order of operations and procedures, and organizational structures.

5.2.1 Pavement Roughness Data-Gathering Stakeholders

Stakeholders in the pavement roughness system include private companies, government organizations, transportation departments, agencies, and individuals who are required for the construction and operation of the pavement roughness data collection system. These stakeholders are outlined and described as follows:

- **Transportation Departments –** The primary user of pavement roughness information will be the agency responsible for the maintenance of the state roadway system; in this case, VDOT.
- **US Department of Transportation –** The USDOT will be responsible for high-level guidance to state agencies when implementing ITS-related systems.

- **Federal Highway Administration –** FHWA currently collects road roughness as a portion of the state reports required annually, and hence is a driver for data collection.
- **Standards Organizations –** Standards organizations such as AASHTO, the American Society of Testing and Materials (ASTM) and Society of Automotive Engineers (SAE) assume responsibility for the development and advancement of standards for probe-vehicle based pavement roughness data gathering systems.
- **Vehicle Drivers -** Sharing roughness information from vehicles may require action on the part of the driver under certain implementation systems.
- **Automobile Manufacturers –** Manufacturers, in response to regulations dictated by government agencies, control vehicle design and by extension the ability of future vehicles to gather and transmit roughness data.
- **Research Institutions –** Research institutions, through research grants by local DOTs and USDOT, continue to research and implement improvement measures.
- **VDOT Contractors –** IRI information is used by VDOT to adjust payments for paving contractors, and contracts with Fugro to provide paving information. The status of VDOT contractors may shift with any new system.

5.2.2 User Activities

This section describes how each user will interact with and support the system, including quality control measures, projecting management, and funding as follows:

State transportation departments are responsible for:

- **Funding –** provide funding for the program on a one-year or recurring basis.

- **Project Management –** determine performance criteria and metrics for success, create reports which measure the system against these metrics, and make changes as appropriate.
- **Quality Control –** determine metrics for data and system quality, and create reports which compare these criteria.
- **Implementation –** Contract with a technology company, or utilize existing human resources, to implement the final system as outlined.
- **Develop Standards –** Develop standards for the data, i.e. required statistical significance and reliability.
- **Equipment Upkeep** - Upkeep of RSUs (as necessary), data processing and storage, end-user interfaces, and integration with existing systems.
- **Probe Vehicles** - Identify and utilize appropriate probe vehicles for program use under certain systems; the connected vehicle approach uses public vehicles.
- **Data Use –** The use of data for pavement maintenance programs.

The USDOT is responsible for:

- **Guidance:** High level guidance to state agencies when implementing ITS-related systems. The ITS programs are run through USDOT's Research and Innovative Technology Administration (RITA), which can provide implementation guidance for state departments of transportation and sponsor research.
- **Support –** RITA's research scientists can provide technical support and systems engineering problem solving to the new program.

- **Monitoring –** Monitor the program's progress and performance data to serve as a test-bed for future connected-vehicle based technology programs.
- **Collaboration** – Interface between local departments of transportation, standards organizations, automobile manufacturers, and the FHWA.

The Federal Highway Administration:

- **Requirements Review –** The FHWA currently requires state DOTs to provide annual reports with IRI; review for relevancy and need for actual IRI data.
- **Guidance –** Guidance and conversation with local DOTs regarding reporting requirements and required data for optimal decision-making.

Standards organizations such as AASHTO, ASTM and SAE are responsible for:

- **Development** - Development of standards for probe-vehicle based pavement roughness data gathering system, or alteration of current standards.
- **Technical Support –** Streamlining message set directories and troubleshooting technical difficulties related to message sets.

Vehicle Drivers will be responsible for:

- **Vehicle Operation -** Managing data collection systems and conforming to instructions for maximizing data quality. This includes driving a near-constant speed or a specific speed for stretches of roadway for the fleet vehicle and mobile device approaches; drivers are unregulated for the connected vehicle method.

Automobile Manufacturers will be responsible for:

- **Design -** Adherence to regulatory regulations and standards as they relate to ITS and the connected vehicle program.
- **Technical Support -** Limited technical support, assisting with modification of vehicle on-board equipment and extracting sensor information.
- **Collaboration –** Working with the USDOT to develop and implement standards, ensure vehicle modifications do not affect safety, and ensure seamless operation.

5.2.3 Order of User Operations

The order of operations outlined below is intended to be a preliminary guide for the order of actions by users to implement the data-gathering system. It is split into the operational order of operations, and in to ongoing process improvement operations, which are conducted simultaneously and in parallel to improve functionality.

Operational Order of Operations:

1) Department of Transportation (local DOT) determines roughness data requirements for a selected time period, including data quality. This will determine required number of probe vehicles, routes, and modes of operation.

2) Required number of probe vehicles prepared from VDOT fleet. This may involve sensor calibration or the installation or purchase of equipment. A several month lead time is ideal for setting requirements. Under the connected vehicle approach, this may include deciding on data collection requirements.

3) Vehicle operators and data processors are informed of requirements, and create driving routes and vehicle assignments to meet these requirements under the fleet vehicle and mobile device approaches.

4) Vehicles gather the necessary data over the time period interval specified, and transmit data back to the central processing unit.

5) On a continuous or time-period specific basis, data processors convert the data into usable indices and/or IRI data, and pass the data on to various stakeholders, including the local DOT, the USDOT, FHWA, and research institutions.

6) A data quality and validation process which verifies the roughness estimation system is working properly. This may include periodically checking fleet-gathered data against contractor-collected data, or testing on pavement with known roughness readings.

5.2.4 Organizational Structure

This section describes the organizational structure of the system as related to agencies and organizations involved through the use of Figure 5.2.4.1 below.

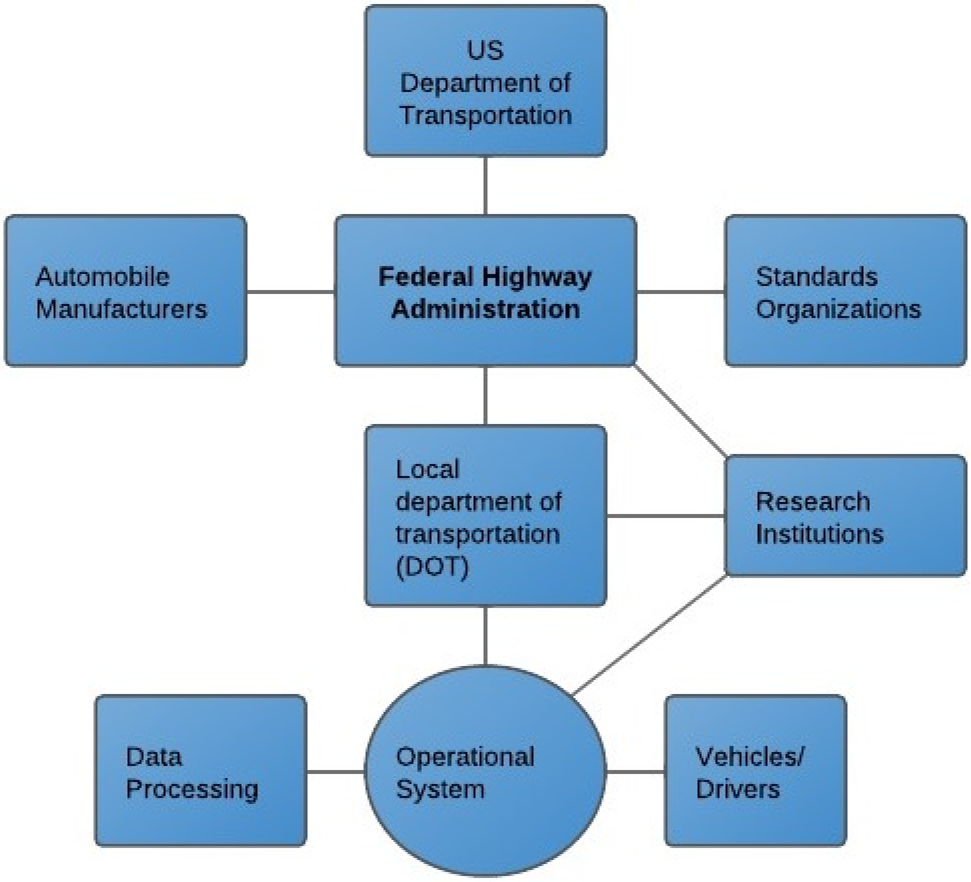

Figure 5.2.4.1: System Organizational Structure

5.3 Operational Needs

This section outlines the goals and objectives of the Virginia Department of Transportation, which will guide requirements for the agency. Under the current system, annual coverage for pavement roughness data is limited to the interstate system, primary roads, and 20% of secondary roads, leading to data which may be up to five years old on some sections of roadway. To make informed and up-to-date maintenance decisions, roughness data should be updated more frequently than is current practice. Operational needs of VDOT are defined as follows:

1) Pavement roughness data on the roadways in Virginia which fall under the maintenance authority of VDOT at least every two weeks to once a month; this is approximately the most frequent useful collection interval.
2) Integration of the new pavement collection system in to existing pavement maintenance decision matrices and/or data collection systems.
3) If private mobile devices are used, ensuring location data and privacy are upheld for mobile users.
4) Low capital and recurring costs in comparison with the current system.

5.4 System Overview

This section provides a description of the relationships of system components, including the scope, interfaces, system capabilities, and objectives of the system.

5.4.1 Interfaces

This section outlines interfaces between individual vehicles and their installed equipment, local or regional data collection center, data processing center, pavement maintenance office at the state DOT, and research institutions in Figure 5.4.2.1 below.

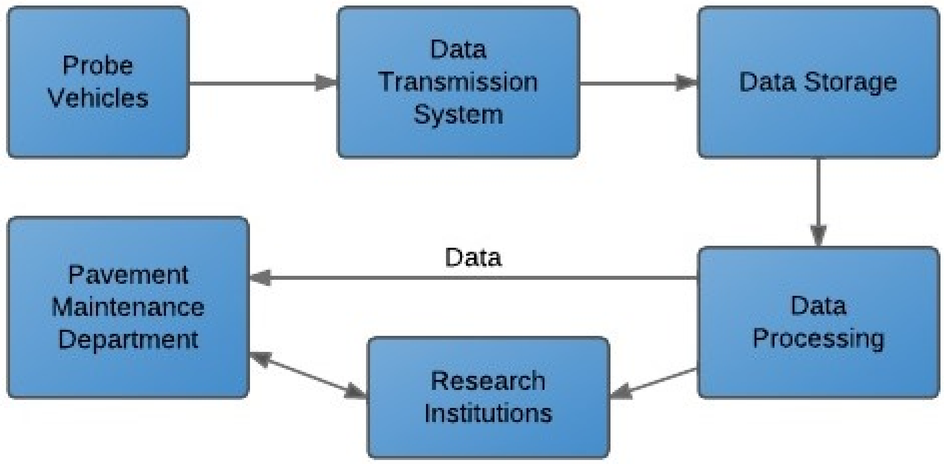

Figure 5.4.1.2: Illustration of Interfaces at the System Level

5.4.2 Goals and Objectives.

1) **Produce Usable Data.** Utilize probe vehicles to collect pavement roughness data on a statewide roadway network, including interstates, primary, secondary, and neighborhood roads, with sufficient frequency to provide daily updates on pavement condition.
2) **Transmit to Database.** Transmit roughness data to a central database for transformation into a meaningful measure of roadway condition, such as IRI or equivalent.
3) **Integrate with Existing Decision Systems.** Roughness estimations by the data gathering system should lead to improved decision-making within the current system, and support future decision-making systems.

5.5 Operational and Support Environments

This section outlines the operational and support environments, including necessary facilities, equipment, hardware, software, and personnel for operation.

5.5.1 Equipment & Capabilities

This section outlines the equipment necessary for implementation of the system, including limited technical requirements.

Probe Vehicles should be capable of traveling distances of at least 200 miles without refueling, and be reliable enough to ensure minimal downtime for maintenance activities.

Accelerometers should have a minimum sensitivity of .02 g, resistance to extreme temperatures (particularly warm temperatures), and be capable of outputting data at sufficient resolution to support the pavement maintenance application; at least 200 Hz.

Data Server should be capable of holding at least 100 TB of information at the regional level, or 500 TB at the state level. It should also be capable of receiving information at 200 mb/s, and possess sufficient processing power to run the algorithms for conversion from roughness data to IRI or other usable function.

On-Board Unit (OBU) installed in probe vehicles should ideally possess the computing power and memory necessary to convert data from vertical acceleration to a usable roughness estimate prior to transmission via wireless infrastructure.

5.5.2 Software

This section outlines the necessary software for system implementation, by task as follows:

Calibration of accelerometers will be necessary for program implementation; depending on the chosen platform; this may involve using prepackaged software available from the accelerometer manufacturer, or a Matlab program from a research institution.

Data Processing will involve the implementation of vertical accelerometer data to usable roughness information algorithms as developed by research institutions.

Data Storage involves the storage of large amounts of information, searchable by date, section of roadway, and roughness data (such as displaying only sections of roadway above a specific roughness). A commercially available database and/or SQL software from an established company should be sufficient, such as Oracle, SAS, or SPSS.

Data Display displays IRI and/or roughness data equivalent in a usable manner. VDOT currently possesses software (WiseCrax) which shows IRI in combination with other forms of information to the user; the system may integrate with this software package as well.

5.5.3 Personnel

This section outlines the necessary personnel for system implementation by role, including personnel who will work in multiple capacities for other agencies or administrations.

Technician – The technician will be employed by the local DOT, and be responsible for day-to-day operations, including monitoring of accelerometers for operation and malfunction, and ensuring information flow from vehicles to data processing to the end user. Additional responsibilities include creating reports for the program coordinator, responding to data requests from researchers and USDOT, upgrading software and maintaining hardware, and overseeing vehicle modifications. Qualifications include database experience, software programming competency, and mechanical ability.

Coordinator – The coordinator will be an existing manager at the local DOT, ideally one already responsible for coordination of pavement data collection. The coordinator will be responsible for overseeing the problem, reviewing reports written by the technician, and providing a vision and direction for the program. They will correspond with researchers, the USDOT, and other participating organizations on process improvement.

Information Technology Support – The IT support staff will be existing support staff at the local DOT, and will assist the technician with the integration of the system into existing information technology systems within the DOT.

5.6 Operational Scenarios

This section of the ConCops will detail system operations from the perspective of various users. User perspectives in the default scenario, plus stress and failure scenarios and multiple other regularly occurring scenarios, provide a description of how the system will work in an easy to follow format.

5.6.1 User Perspectives

Transportation Departments will utilize this data in a similar manner to maintenance gathered by the current contractor, except that instead of pavement deterioration models for sections of pavement which have been covered only once every five years in the past, up-to-date roughness data can be substituted. Transportation departments can make requests of research institutions and/or the USDOT if data does not prove helpful and work to develop incremental improvements. Transportation departments will also look at their data-gathering requirements and relax standards where applicable for use within the data-gathering program.

US Department of Transportation – The USDOT will oversee this program and monitor for success using developed metrics, then utilize portions of the program's implementation process for future ITS-enabled programs. If the program does not prove successful or helpful, these lessons can be written into future implementation guidance. If the program succeeds, it can be expanded to cover multiple states or regions in the United States by the USDOT with the help of the FHWA and local DOTs

The Federal Highway Administration – FHWA currently collects road roughness as a portion of state annual reports, and hence is a driver for roughness data collection. The FHWA should reevaluate roughness reporting requirements in an attempt to accept data from the new probe-vehicle based system.

Standards Organizations – In the default scenario, AASHTO, ASTM and the SAE will monitor progress of the pavement roughness program and make recommendations for standardization, eventually creating a standard for vertical accelerometer-based roughness measurement, similar to the quarter-car model used today.

Vehicle Drivers – Vehicle drivers will receive their instructions from the technician overseeing the program. Ideally the drivers are DOT employees who are traveling to their daily assignments, managers traveling between offices, or maintenance or technicians traveling to repair stoplights, overhead signs, or other infrastructure. Intrusion of the data gathering technology will be minimal; ideally the system will be fully integrated into the vehicle, so drivers are spared the memory item of beginning and ending the data gathering program when driving from point to point. Occasionally a driver may be asked to drive slightly out of the way to gather additional information if a coverage area is less than normal.

Automobile Manufacturers – Manufacturers may be asked by researchers, the FHWA, or the USDOT to provide technical assistance for the modification of on-board equipment or processors, and the extraction of information from accelerometers incorporated into vehicle systems, etc. Limited participation is expected from automobile manufacturers, as there is no incentive for them to participate or modify their vehicles.

Research Institutions – Research institutions will be receiving a constant flow of data from the data processing center and the DOT, and researchers may choose to use a portion of the data for testing. Additionally, stock units from the USDOT can be tested for functionality, particularly on a track such as the one available at Auburn University.

5.6.2 Stress/Failure Scenarios

The relatively large scale of the system on a statewide level, combined with its many components and probe-vehicles, means there are many variables which can cause stress on the system. The first potential cause of stress will be when all data-gathering vehicle probes are transmitting roughness data simultaneously, such as during the morning and evening rush hour. This scenario creates daily “peaks” of information and strain on the data transmission, storage, and processing capacities of the system. Second, server or data processing unit downtime will create a cascading effect as mobile units must store roughness data instead of transmitting. When services come back online, units will upload data simultaneously, creating a high system load.

Other types of failure may be more difficult to detect. For example, if a vehicle’s dynamic characteristics change over time due to wear on vehicle components, the incoming data will appear normal. The same is true for sensor mounts which break in normal operation, in poor weather, and multiple other scenarios. Although this does not amount to system ‘failure,’ it means the incoming data is not correct or accurate, and should not be used for maintenance decisions. Regular vehicle inspections, software analysis, or a quality control system which regularly assesses stretches of pavement with conventional means and compares with the probe vehicle estimation system should be integrated with any system to prevent deterioration of data quality over time.

Chapter 6: Conclusions

This chapter discusses the information presented and analyzed throughout the body of the report and presents a list of advantages and disadvantages for each approach in table form. Further, it presents conclusions in the form of implementation scenarios and timelines, and offers suggestions for further research.

6.1 Research Conclusions

The technical implementation of a large-scale system designed to capture roughness data from vehicular motion through the use of accelerometers is possible. Several research projects, one at the University of Auburn and one at the University of Michigan Transportation Research Institute, have proven the feasibility of converting accelerometer data into usable information on the condition of the road surface. Each option presents advantages and disadvantages, as outlined in the table below:

Connected Vehicle Approach	
Advantages	**Disadvantages**
• Capitalizes on infrastructure of proposed connected vehicle system • Potentially large market penetration • Capable of eventually provide hourly roughness updates • May eventually utilize OEM equipment, limiting costs • Data usable with current roughness indicators	• Currently limited by standards and lack of infrastructure • Vehicle modification, if required, is expensive and difficult • Generates largest amount of data of the three; may require additional measures for selective sampling • Data may be affected by vehicle modifications
Fleet Vehicle Approach	
Advantages	**Disadvantages**
• Ready for implementation now • Data usable with current roughness measures • Can utilize existing commercial wireless network infrastructure • Probe vehicles can be monitored and	• Large capital costs • Relatively small fleet; potentially inconsistent and infrequent coverage • Equipment and time intensive

equipment controlled	
Smartphone Approach	
Advantages	**Disadvantages**
• Ready for implementation with little additional research • Utilizes devices with a large and expanding market share • Cost effective if private users can be involved	• Data output requires additional study before proven useful • Private vehicle owners have no incentive to operate application • Inconsistent coverage

Table 1: Advantages and Disadvantages of System Approaches

Each system offers a unique set of tradeoffs which should be considered when implementing a roughness assessment program, and predominantly depends on the timeline in which decision-makers would like to operate. Short term, the "ready now" aspect of the fleet vehicle approach allows immediate implementation. Looking to the future, the smartphone approach would be most applicable for implementation in several years, and the connected vehicle system could prove the best choice in the long term.

The fleet vehicle approach has been proven to produce usable results by Auburn researchers; all that remains is a way to transmit usable data to a central server. Thus, the installation of semi-permanently and calibrated 3- or 6-axis accelerometers in a limited vehicle fleet, paired with a 3G wireless connection, is currently the most effective way to add value to decision-making at the VDOT, as it results in roughness information which can be translated to an IRI estimate with a minimum of effort.

Currently, the use of roughness data gathered from smartphone accelerometers which are mounted to the windshield of the vehicle by the casual user has limited value for VDOT's purposes. UMTRI is currently researching methods of extracting useful roughness information from data, and thus smartphone data could prove an effective pavement maintenance measure in the future. Additionally, the application requires further modification prior to mainstream approval; the ability to run the application without a Bluetooth interface for the OBD II port would dramatically increase its utility.

In the current iteration of ITS and the Society of Automotive Engineer's J2735 standardized message set for surface vehicles, the implementation of a large-scale road roughness data-gathering application is not feasible. The system has been designed from the ground up for safety and efficiency, and continuous collection of roughness data is not easily compatible with its system design. The high volume of data, combined with the infrequent placement of road-side unit receivers and the "snapshot" data save and transmission intervals outlined in J2735, surpasses the abilities of the base system without some modification. Future iterations of ITS, or vehicles with OBEs specifically modified to capture sensor data at higher resolution, may allow the V2I component of ITS to function as a conduit for roughness data. As such, this approach is most suited to long term implementation strategies.

6.2 Future Research

Future research should focus on the practical aspects of implementing a widespread system. First, look at future revisions to the J2735 standard and vehicle technology to determine if the standard-based barriers to a vehicle-based pavement roughness data gathering application have been removed or lowered. Second, construct an in-vehicle system which uses mounted accelerometers, such as in the fleet vehicle approach, and sends the data over an existing wireless network while minimizing equipment bulk, costs, and setup time in the vehicle. Third, research improving the ability of smartphones to capture pavement roughness through innovative in-vehicle mounting techniques, data analysis, conversion algorithms (post processing), or develop applications which produce usable data in real-time. Fourth, determine the number of readings required to produce a reasonable estimate of pavement roughness. Lastly, research the use of roughness measurements to detect when pavement is deteriorating to the point of requiring maintenance, and the long-term analysis of trends to recognize various types of deterioration based on speed of decay and traffic information.

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