EXAMINING THE ADOPTION OF SATELLITE-BASED REAL-TIME WEATHER HAZARD TECHNOLOGY IN THE VIRGINIA ROADWAY TRANSPORTATION SYSTEM

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By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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SATELLITE-BASED REAL-TIME WEATHER DATA TECHNOLOGY

The technical project will focus on creating a conceptual design for a remote-sensing spacecraft to aid in real-time weather data collection to improve roadway safety. The STS research topic is tightly coupled, as it focuses on the wide-scale adoption of this same technology in the Virginia roadway transportation system.

While there is ongoing research into using real-time weather data from satellites to improve roadway safety, this technology is still far from being adopted on a large scale. It is useful to understand the adoption process so that problems can be solved where they arise. This STS research paper analyzes the adoption process within the Diffusion of Innovation social framework to identify where and why barriers to adoption exist in the transportation system, and aims to provide reasonable solutions to them.

THE DIFFUSION OF INNOVATION FRAMEWORK

In E.M. Rogers' Diffusion of Innovation model, new technologies are adopted first by a small group of innovators, then a larger number of early adopters, then the early majority of users, followed by the late majority and the laggards. The order of adopters increases chronologically with their propensity to resist adoption. Under the model, the ease and ability to adopt a technology is dependent on five factors: the technology's competitive advantage, its compatibility with the needs and wants of adopters, its complexity, its trialability, and its ability to provide observable results. The adoption process also consists of five stages, starting with an adopter's awareness of the technology, their interest in it, a positive evaluation of it, the act of trying it out, and finally the adoption of it (Rogers, 2003).

IMPACT OF WEATHER ROADWAY HAZARDS

The significance of weather-related roadway hazards is apparent; weather hazards create dangerous driving conditions, which leads to vehicular crashes. Crashes compromise driver safety and also constitute an economic cost, amounting to $6.8 billion in Virginia in 2018 (TRIP, 2020). Businesses incur an economic cost as well since hazardous conditions stimy transport and supply capabilities, while crashes and congestion foster poor public opinion towards transportation agencies and legislators. Consequently, the benefits of having a centralized system providing real-time weather-related data are also apparent. By providing up-to-date information quickly to drivers, stakeholders have more time to react to adverse conditions and needless weather-related crashes can be prevented. Adopting a dedicated satellite system would improve the gap in real-time weather hazard reporting, which would be beneficial across the board as shown in Figure 1.

Stakeholder	**Effect of Weather-Related Roadway Hazards**	**Effect of Real-Time Weather Data**
Drivers	Compromises safety	Ability to prepare/adjust behavior
General public	Compromises safety	Ability to prepare/adjust behavior
	Economic cost from crashes	Reduces economic cost due to less crashes
Transportation agencies	Compromises safety/integrity of roads	Can provide information faster and address hazards
	Clogs transportation management efforts	Quicker implementation of solutions
	Crashes lead to negative public opinion	Improved opinions due to less crashes & congestion
Businesses	Detriment to supply/transport	Hazard information improves supply/transport capabilities
Legislators	Crashes lead to negative public opinion	Improved opinions due to less crashes & congestion
Navigation apps	Inability to provide information valuable to customers	Competitive advantage in providing desirable features

Figure 1: Effect of Weather-Related Roadway Hazards and Real-Time Weather Data on Stakeholders. This figure lists the effects of weather-related roadway hazards and access to reliable real-time weather data on various stakeholders in the roadway transportation system. (Created by Isaac Burkhalter, 2021).

The research paper will first focus on developing the Diffusion of Innovation model for satellite technology as a whole, and determining where the adoption of real-time weather data technology by roadway transportation systems falls. In this context, the research will focus on the situation and complications surrounding the use of real-time weather data. Methods by which the Virginia transportation system can adopt this technology will then be analyzed through the Diffusion of Innovation framework to identify barriers to adoption and propose ways to overcome them.

HISTORY OF SATELLITE TECHNOLOGY

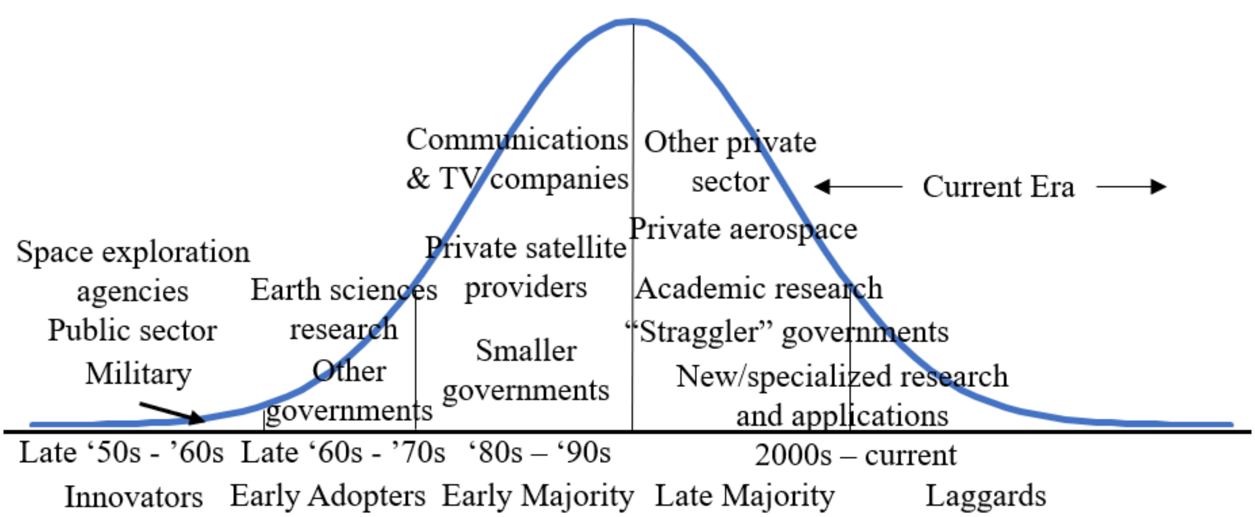

Figure 2: Diffusion of Innovation Model of the Adoption of Satellite Technology. This figure shows the major adopters of satellite technology at each stage of adoption in the Diffusion of Innovation framework. (Created by Isaac Burkhalter, 2021).

Since this paper concerns the introduction and application of new satellite technology, it is useful to look at the history of satellites as a whole. Figure 2 depicts this model of adoption as it applies to satellite technology, with the proportion of adopters in each section equating to roughly one standard deviation under a Gaussian curve.

Developing and launching satellites had enormous economic and logistic barriers to entry, and the success of initial adoption in the late 1950s was heavily tied to the space race. The first launch was only possible with a federal backing, so naturally federal space exploration programs such as those under NASA and the Soviet Space Program could be considered the primary innovators. Several early satellites focused on observing the Earth from low earth orbit, so public research agencies can be considered early innovators as well, although it should be noted that these efforts were still heavily tied to space exploration agencies. Several communications satellites were launched in the early 1960s, which were of interest to the public sector and the military (National Aeronautics and Space Administration, Jet Propulsion Laboratory [NASA JPL], 2014). Additionally, though satellite reconnaissance capabilities were not fully developed during the initial adoption stage, the possibility was undoubtedly a driver for adoption, so the military can be considered an innovator in this sense as well (de Gouyon Matignon, 2020). From the late 1960s through the 1970s, other governments, in particular those of several Western European and Asian countries, chased the same satellite capabilities and became early adopters of the technology (NASA JPL, 2014).

The real boom in satellite technology adoption by the early majority came in the 1980s and 1990s. Smaller governments raced to catch up and launch their own satellites. With improvements in communications technologies during this era, including cable and satellite television, telecommunications, and data services, the need for communication satellites skyrocketed. Communications and television broadcast companies entered the mix in force, and some satellite providers like Intelsat and PanAmSat began to break into the private sector

(Broadband Wherever, 2014). The 21st century can roughly be considered the late majority period of adoption. Governments that had not yet launched their first satellites have gradually been doing so (Broadband Wherever, 2014). In addition, the internet age further drove innovations in internet technology, broadband and mobile services, and data transfer speeds, which subsequently drove demand for satellites within the private sector (Iida, Pelton, & Ashford, 2003, pp. 2-10). The 21st century has seen contractors such as Lockheed Martin, Boeing, and Northrup Grumman, as well as newer private ventures such as SpaceX, break into the satellite industry (Sheetz, 2019).

Although the future is uncertain, it is likely that the present lies somewhere between the late stages of the late majority and the early stage of "laggards". Many adopters are finally able to use satellite technology; for one because of the number of satellites launched, and more importantly because of decreasing production costs. Governments that have previously not launched satellites have been taking the initiative to do so, such as those in Africa, the Middle East, and Central Asia (Broadband Wherever, 2014). The development of CubeSats, or lower cost miniature satellites, have enabled space-based academic research, particularly in the past fifteen years. Lower costs have also enabled new or more specialized research and applications of satellite technology.

ISSUES WITH CURRENT METHODS

This stage of adoption is the context in which the satellite-based real-time weather data technology is being introduced. The concept itself is being actively verified via academic research at UVA; my technical team is working on a conceptual CubeSat launch that will, with luck, be launched within the next few years. The issue of this paper, however, focuses on the adoption and application of this technology by transportation stakeholders. The lack of a system to provide centralized real-time weather data has a negative impact across the board. The Virginia Department of Transportation [VDOT] and other state and federal transportation agencies have access to weather data. However, the important information to them is the actual road condition measurements that result from weather hazards. Currently, this information is gathered via ground-based systems, quite often by using on-site manual evaluation techniques. While cost-effective, this is localized and can be laborious and time consuming (V. Lakshmi, personal communication, October 14, 2020). There is no existing system-wide solution to obtain road condition measurements that is consistent and in real-time, so data can be out of date or simply not exist in certain areas.

Information on weather-related road hazards can then be relayed to drivers through channels such as the Virginia 511 service, local media, or navigation apps like Waze. These all have inherent issues, however. Through Virginia 511, VDOT sends weather hazard warnings to electronic signs on well-travelled roads. This only applies on a limited number of roads, though, and information may be out of date. Drivers must also already be out on the road before seeing the warnings. Drivers can receive warnings through information relayed to local media before heading out, but these outlets usually only report on the most severe cases. Navigation apps are seemingly a great option for drivers to check road conditions, but many do not include weather data in their algorithms. For the ones that do, different algorithms may lead to conflicting conclusions, and the information shown suffers from the same inherent flaws as the information sent from VDOT in the first place (M. Fontaine, personal communication, October 28, 2020).

ADOPTION CHANNELS AND BARRIERS TO ADOPTION

The cost of implementing real-time satellite technology is well within the budget of both state and federal transportation agencies. Thus, the research question arises: given the benefits of real-time weather data satellite-based technologies, why do barriers to adoption still exist among transportation stakeholders, and how can we overcome them? To examine this question, it is useful to first take a business approach. If the satellite system is viewed through the lens of a new product, one fact becomes immediately clear: not all end users can actually buy the product. A satellite system is prohibitively expensive, and your average automobile driver would not be able to purchase the system itself in order to use its data. Thus, the relevant barriers to adoption are likely related to the stakeholders with purchasing power, or the so-called "economic buyers" and "decision makers", as well as those around them (Blank & Dorf, 2012). Of the stakeholders mentioned previously, the only ones with such buying power are state and federal transportation agencies who have access to government funds, such as VDOT. The research henceforth focuses on analyzing these transportation agencies and several potential channels for adoption to analyze how barriers arise.

The first channel VDOT can pursue is a partnership with academic research centers and universities. A great example of this is the Virginia Smart Road partnership with the Virginia Tech Transportation which launched in 2000. The partnership enabled the advanced testing of ground-based solutions, which VDOT could then begin integrating into their own roadway management practices (Virginia Tech Transportation Institute, 2021). Satellite technologies differ in one major way, however. While proof of concept can be proven through low-cost research projects such as those using CubeSats, actually testing satellite observation systems requires a larger amount of funding. If VDOT were to fund these efforts themselves, it would require a significant reallocation of resources away from their highway maintenance and operating funds. Without further action VDOT would be unlikely to pursue testing, hence a lack of trialability would act as a barrier to adoption.

This could be solved by obtaining federal funds, the model for which is shown in Figure 3. Obtaining funds, however, is a process surrounded by bureaucratic red tape. VDOT would need to draft a work program, get federal approval, finalize an agreement, and then provide periodic reports on the project (VDOT, 2018). The process would still require a reallocation of funds, both for VDOT's annual allocated federal funds specifically and potentially for funding at the federal level as a whole. Lack of interest could be a barrier to adoption in this case. Additionally, VDOT currently does not have a dedicated satellite research program, so it is likely that any immediate research would be a subset of one of its existing programs. The lack of simplicity of this channel could also act as a major barrier.

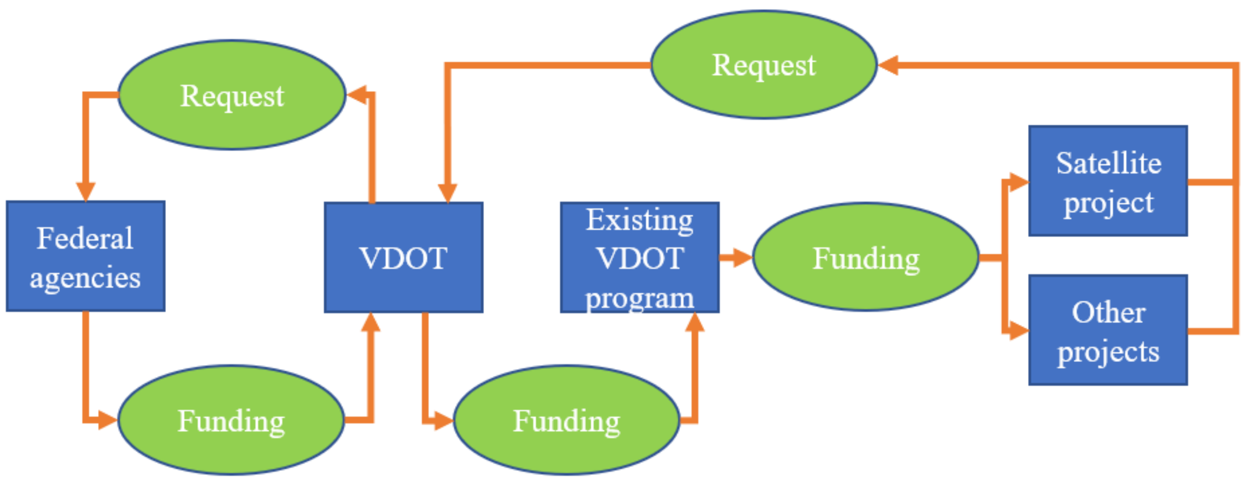

Figure 3: Model for Obtaining Federal Funds for a VDOT Project. This figure shows a model of how federal funds are obtained and allocated when requesting funds for the real-time weather data satellite project. (Created by Isaac Burkhalter, 2021).

VDOT could also potentially partner with a federally established program to accelerate in-state research. Transportation-specific federal programs involving satellite technology exist, for example the Commercial Remote Sensing and Spatial Information Technologies Program established by the US Department of Transportation. From 2006 to 2012, however, the program only received around $38.7 million; a relatively small amount for space-related research (US Department of Transportation, 2020). Conversely, the need for real-time earth observation via satellite technology has been recognized by scientist as it relates to climate change and weather phenomena, with many scientists stressing the need for a unified plan to develop these capabilities (Chatterjee, Collins, Crisp, & Majumdar, 2021). The results of this awareness are clear, with NASA's requested 2021 earth and planetary science budget being around $1.8 and $2.7 billion, respectively (NASA, 2020). The level of awareness and interest in the transportation applications of real-time observation pale in comparison, which creates a significant barrier to the adoption of these technologies at a federal level.

Finally, VDOT could attempt to contract the technology to an outside company. This would be along the lines of my technical project, where we are partnering with MITRE to design a CubeSat. Assuming the research is fruitful, MITRE could continue the research and work with VDOT to try and implement it. Contracting could be performed through a design-build contract, which may still require approval for federal aid through agencies such as the Federal Highway Administration (VDOT, 2017). This method does have the advantage of an external third party working on developing the new technology, but it is also a more passive stance for VDOT to take.

POTENTIAL SOLUTIONS

From the evidence, the barriers to a state-wide adoption of a satellite system providing real-time weather data can be summed as follows: lack of interest or awareness in transportation-related applications of satellite technology, limited trialability due to large funding needs, and complexities in acquiring the necessary funding. To address these issues, two system-wide solutions come to mind. First, improving access to information at all levels would increase interest and awareness, and would accelerate research efforts. While climate and earth scientists may not have much interest in transportation issues, much of the research and experimentation in their fields concerning real-time earth observation is directly applicable to real-time weather data use in transportation.

The second solution is more difficult to implement as it involves a change in structure, but it is more effective as a whole. By reorganizing satellite-based technology development into a centralized top-down structure the flow of information could be improved, the interests of lesser-known stakeholders would be considered at the top levels, receiving federal funding would be greatly facilitated, and trialability at the lower levels would be increased as part of a larger connected system. This method can be applied at both the federal and state level, as shown in Figure 4. To explain the effects of this solution, the adoption of satellite-based real-time observation technology was reframed using DOI. If a broader federal satellite program was created, those under the program could be considered the innovators who initiate projects and have access to funding. Programs under large federal agencies, such as the US Department of Transportation [DOT], would be the early adopters who obtain funding and research data from the federal program. Programs under related state agencies such as VDOT would be majority adopters, and funding could be more easily acquired through the wider US DOT program. Furthermore, by consolidating satellite-based development under VDOT into a single program, the allocation of funding to different projects would be greatly simplified. For example, SAR, InSAR, and optical sensors can potentially be used on satellites to monitor large roadway infrastructures in real-time (Vaghefi et. al, 2012, pp. 888-892). VDOT could fund both this project and the real-time weather data project though a centralized satellite program, rather than through separate roadway infrastructure maintenance and weather hazard programs.

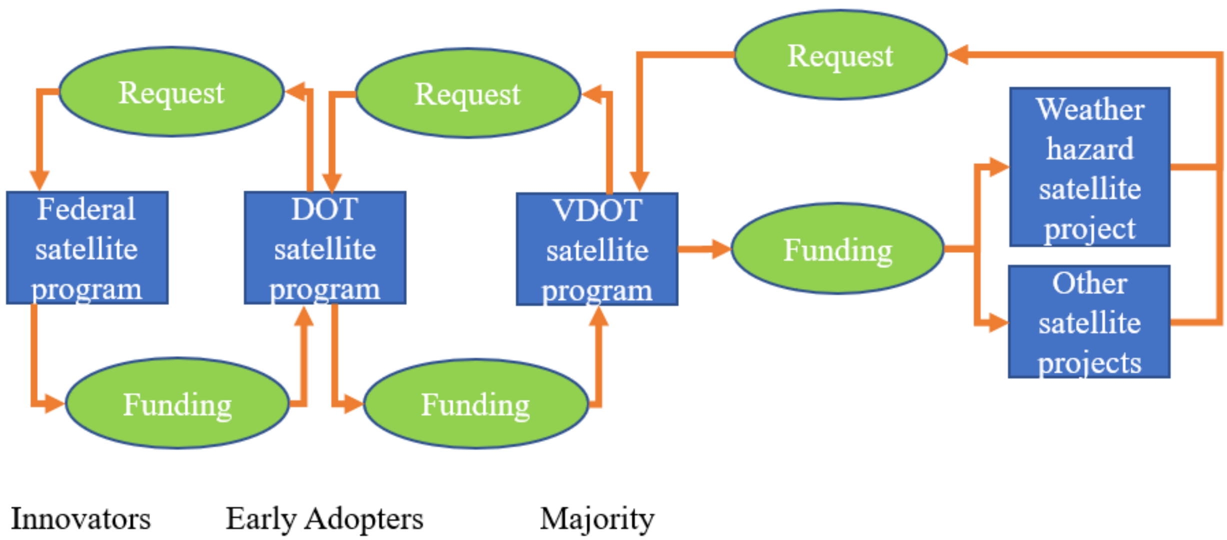

Figure 4: Obtaining Funds in a Centralized Top-Down Model. This figure shows the process of requesting, obtaining, and allocating funds in the proposed centralized top-down satellite program model. (Created by Isaac Burkhalter, 2021).

OVERCOMING BARRIERS TO ADOPTION IN THE VIRGINIA ROADWAY SYSTEM

The Virginia transportation system is a late adopter of satellite technology due to significant barriers. For satellite-based real time weather hazard technology in particular, the technology suffers from a lack of interest, low trialability, and a high level of complexity. These barriers can be lessened by improving information sharing at federal and state-wide levels, and by consolidating satellite programs into a centralized top-down model. Further research into applying the top-down model and identifying alternative solutions could help further remove barriers to adoption.

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