IMPLEMENTATION OF WIRELESS AND SENSING TECHNOLOGIES IN HIGHWAY PROJECTS: A SWOT APPROACH

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Abstract
The demand for safe, reliable, and higher-quality transportation and infrastructure systems often increases the complexity of constructing and maintaining highway projects and pressures Departments of Transportation (DOTs) to finish projects on tighter schedules and stricter budgets. Such complexities necessitate the use of technologies when constructing and maintaining transportation assets, notably wireless and sensing technologies. For the last few years, DOTs' use of wireless and sensing technologies has been on the rise, with numerous research efforts aiming to explore applications and investigate case studies. Thus, this study builds on the existing body of knowledge to develop a holistic Strengths Weaknesses Opportunities Threats (SWOT) framework that aims to comprehensively understand the implementation of eight wireless and sensing technologies in highway projects including barcodes and readers, Radio Frequency Identification (RFID), e-ticketing, Ground Penetrating Radar (GPR), Unmanned Aerial Systems (UAS) or Vehicles (UAV) or Drones, Light Detection and Ranging (LiDAR), Geographic Information System (GIS), and Global Positioning System or Global Navigation Satellite System (GNSS). The SWOT framework was developed via literature and then distributed via an online survey to subject matter experts in different DOTs. Results from the survey provided comprehensive insights into the strengths of using the technologies in the project's construction and asset management phases, the weaknesses that these technologies may face, the opportunities that they provide DOTs with, and the threats that the DOTs may need to overcome for successful implementation.

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1. Introduction
State Departments of Transportation (DOTs) across the United States have been undergoing major transformations to adopt technology and digitize the design, construction, delivery, and operation of construction projects [1]–[3]. Such transformations have rapidly accelerated in the last few years with the national push to digitize asset data and the increase in investments to repair and renew the aging infrastructure [4], [5].

Wireless and sensing technologies are at the forefront of the technologies making waves in infrastructure projects due to the critical role they play in monitoring, managing, and maintaining existing transportation assets [5]–[7]. Moreover, the success of complex infrastructure projects requires project information and data to be accurate, complete, readily available, gathered promptly, shared in an easily understood format among stakeholders, and stored safely and securely – paving the way for the diverse use of wireless and sensing technologies [8], [9].

State DOTs have been adopting and using wireless and sensing technologies in various use cases that enable them to identify, gather, locate, track, measure, save, document, and transmit information in real-time or near real-time [10]. With this adoption expected to increase, the objective of this paper is to understand DOTs' experience with wireless and sensing technologies and provide insights into the technologies' roles in highway infrastructure projects.
2. Research Methodology

This paper focuses on eight technologies that have gained traction within state DOTs: barcodes and readers, Radio Frequency Identification (RFID), e-ticketing, Ground Penetrating Radar (GPR), Unmanned Aerial Systems (UAS) or Vehicles (UAV) or Drones, Light Detection and Ranging (LiDAR), Geographic Information System (GIS), and Global Positioning System or Global Navigation Satellite System (GNSS). To achieve the research objective, a comprehensive SWOT framework was developed to identify the:

- Strengths of using each of the technologies in the construction and asset management phases of the project;
- Weaknesses that these technologies may face;
- Opportunities that they provide DOTs with;
- Threats that the DOTs may need to overcome for successful implementation.

A survey was developed and shared with subject-matter experts across the different DOTs through the AASHTO Committee on Construction, AASHTO Committee on Maintenance, and the AASHTO Subcommittee on Asset Management. The survey aimed to collect data on each aspect of the SWOT framework. Statistical tests were then performed to analyze findings and draw conclusions.

2.1. The SWOT Framework

SWOT framework is a simple yet powerful tool that can be used by decision-makers in the early stages of business planning to develop strategies and support decision-making [11], [12]. Strengths and weaknesses are internal factors, while opportunities and threats have an external nature [11], [12]. SWOT analysis has been extensively used in research studies targeting different industries such as oil and gas, mining, manufacturing, agriculture, transportation, food and nutrition, and construction [13], [14]. In the context of adopting technologies in the construction industry, SWOT analysis can provide organizations with a deep understanding of the possibilities of exploiting the technology’s strengths and overcoming its weaknesses to take advantage of the opportunities it provides to the organization while limiting the risks that it can bring [12]. As such, the internal factors of SWOT – i.e., strengths and weaknesses – are directly related to the technology itself, while the external factors – i.e., opportunities and threats – relate to the context of the application of the technology in construction organizations [15].

The ability of the SWOT technique to address and analyze both internal and external factors makes it highly suitable for providing construction academicians and practitioners with a holistic review of the technology and its applications [15]. Examples of using SWOT analysis for construction technologies include Building Information Modeling (BIM) [12], machine learning [16], blockchain [17], [18], robotics and drones [19], and virtual reality [20]. As the method is deemed successful in construction research, this paper employs SWOT analysis to provide a holistic review of the use of wireless and sensing technologies in highway projects. To identify the SWOT aspects affecting each of the eight technologies targeted in this study, a general framework was comprehensively developed from existing state-of-adoption research on the topic [10], [21].

2.1.1. Strengths

Strengths are regarded as the internal factors that render wireless and sensing technologies important in highway projects. This can translate to the major use cases that the technologies can add value when used across the lifecycle of highway projects. For the strength aspect, two major project phases were considered: construction and asset management. The strength of sensing and wireless technologies depends on their application through the construction project lifecycle, but the nature of the work performed during construction is different from that performed during asset management. Thus, to better analyze the impact of sensing and wireless technologies, the strengths that such technologies bring to the construction and asset management phases were extensively identified as presented in Table 1.
Table 1. Strengths of wireless and sensing technologies.

<table>
<thead>
<tr>
<th>Code</th>
<th>Strengths</th>
<th>Code</th>
<th>Strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-C1</td>
<td>Tracking position of bulk material in transit or for haul route compliance</td>
<td>S-C21</td>
<td>Locating rebar</td>
</tr>
<tr>
<td>S-C2</td>
<td>Tracking of finished materials and inventory</td>
<td>S-C22</td>
<td>Finding underground voids</td>
</tr>
<tr>
<td>S-C3</td>
<td>Monitoring or determining project progress/production</td>
<td>S-C23</td>
<td>Erosion control inspection</td>
</tr>
<tr>
<td>S-C4</td>
<td>Locating haulers at fixed points (plant/ project/ paver/ dump location)</td>
<td>S-C24</td>
<td>Measuring spot temperatures</td>
</tr>
<tr>
<td>S-C5</td>
<td>Locating underground utilities and assets</td>
<td>S-C25</td>
<td>Creating temperature map</td>
</tr>
<tr>
<td>S-C6</td>
<td>Density measurements</td>
<td>S-A1</td>
<td>Locating pavement/material placement for performance tracking</td>
</tr>
<tr>
<td>S-C7</td>
<td>Thickness measurement of pavements</td>
<td>S-A2</td>
<td>Sign, culvert, and other asset inventories</td>
</tr>
<tr>
<td>S-C8</td>
<td>Tracking and monitoring construction vehicles and equipment on site</td>
<td>S-A3</td>
<td>Sharing asset information between different functional units</td>
</tr>
<tr>
<td>S-C9</td>
<td>Tool tracking/ Theft control</td>
<td>S-A4</td>
<td>Pavement crack and defect detection</td>
</tr>
<tr>
<td>S-C10</td>
<td>Documenting material quantities for pay</td>
<td>S-A5</td>
<td>Sign, culvert, and another asset inspection</td>
</tr>
<tr>
<td>S-C11</td>
<td>Smart Work Zone</td>
<td>S-A6</td>
<td>Structure inspection</td>
</tr>
<tr>
<td>S-C12</td>
<td>Automated Machine Guidance</td>
<td>S-A7</td>
<td>Slope stability &amp; landslide assessment</td>
</tr>
<tr>
<td>S-C13</td>
<td>Developing 3D as-built models</td>
<td>S-A8</td>
<td>Location of voids</td>
</tr>
<tr>
<td>S-C14</td>
<td>Collecting as-built information/ mapping of assets</td>
<td>S-A9</td>
<td>Location of buried assets</td>
</tr>
<tr>
<td>S-C15</td>
<td>Site photos &amp; videos</td>
<td>S-A10</td>
<td>Rebar deterioration</td>
</tr>
<tr>
<td>S-C16</td>
<td>Structural inspection</td>
<td>S-A11</td>
<td>As-built development</td>
</tr>
<tr>
<td>S-C17</td>
<td>Remote (underground or confined space) inspection or modeling</td>
<td>S-A12</td>
<td>Guardrail assessment</td>
</tr>
<tr>
<td>S-C18</td>
<td>Earthwork inspection and quantities</td>
<td>S-A13</td>
<td>Site/ Right-of-Way (ROW) Survey</td>
</tr>
<tr>
<td>S-C19</td>
<td>Creating terrain models</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1.2. Weaknesses

Weaknesses, like strengths, are internal factors that are directly related to the use of wireless and sensing technologies. However, unlike strengths, weaknesses reflect the hardships, limitations, or technical breakdowns that the technologies may run into. The weaknesses are presented in Table 2.

Table 2. Weaknesses of wireless and sensing technologies.

<table>
<thead>
<tr>
<th>Code</th>
<th>Weaknesses</th>
<th>Code</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Loss of connectivity</td>
<td>W4</td>
<td>Integrating with current project administration systems</td>
</tr>
<tr>
<td>W2</td>
<td>System Defects</td>
<td>W5</td>
<td>Integrating with plant/supplier information technology (IT) system</td>
</tr>
<tr>
<td>W3</td>
<td>Accessibility for users</td>
<td>W6</td>
<td>Data transfer and interoperability issues</td>
</tr>
</tbody>
</table>

2.1.3. Opportunities

Opportunities are external factors that reflect the benefits and positive aspects that wireless and sensing technologies provide to DOTs. Nine opportunities were identified and listed in Table 3.

Table 3. Opportunities of wireless and sensing technologies.

<table>
<thead>
<tr>
<th>Code</th>
<th>Opportunities</th>
<th>Code</th>
<th>Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>Quality Improvement</td>
<td>O6</td>
<td>Safety Enhancement</td>
</tr>
<tr>
<td>O2</td>
<td>Data Collection, Integration, and Management</td>
<td>O7</td>
<td>Cost Reductions</td>
</tr>
<tr>
<td>O3</td>
<td>Tracking Capabilities</td>
<td>O8</td>
<td>Schedule Acceleration</td>
</tr>
<tr>
<td>O4</td>
<td>Efficiency/Productivity Enhancement</td>
<td>O9</td>
<td>Decision-Making Enhancement</td>
</tr>
<tr>
<td>O5</td>
<td>Communication Effectiveness</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.1.4. Threats

Threats are external factors that reflect the negative aspects that may hinder using the wireless and sensing technologies as well as challenges that organizations may need to overcome for successful technology implementation. Six threats were identified and listed in Table 4.

Table 4. Threats of wireless and sensing technologies.

<table>
<thead>
<tr>
<th>Code</th>
<th>Threats</th>
<th>Code</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Resistance from third parties and vendors</td>
<td>T4</td>
<td>Lack of needed support technology</td>
</tr>
<tr>
<td>T2</td>
<td>Workforce skillset limitations or resistance</td>
<td>T5</td>
<td>Organizational culture (non-tech oriented)</td>
</tr>
<tr>
<td>T3</td>
<td>Investment costs or unknown return on investment</td>
<td>T6</td>
<td>Policy/regulation restrictions</td>
</tr>
</tbody>
</table>

2.2. Chi-Squared Test for Equal Likelihood

To examine if the eight sensing and wireless technologies identified in this study perform similarly across the four components of SWOT, the Chi-Squared Test for Equal Likelihood was employed. The data was organized into contingency tables for every SWOT category and the analysis was performed via R studio to detect significance with a 95% confidence level.

3. Results

A total of 24 responses were gathered from the 19 DOTs as highlighted in Figure 2. Almost half the respondents (50%) worked in the construction division, while the other half varied between asset management and maintenance (21%), IT (5%), across the three divisions (12%), or other divisions (12%) including design, surveying, and project delivery. As for the respondents’ roles, most of them were construction engineers or engineering managers (54%), followed by technical support (9%), material engineers (4%), and other roles (33%) including system chiefs, innovation engineers, researchers, and maintenance engineers.

![Figure 1 Distribution of survey responses (created with MapChart.net).](image)

3.1. Results for Strengths

The distribution of strengths regarding “construction” is shown in Figure 3, while the distribution of strengths for “asset management” is shown in Figure 4.

Based on the normalized heatmap of the construction phase (Figure 3), GPS/GNSS, GIS, and UAV/UAS were the three technologies with the widest range of strengths, with results showing that GPS/GNSS...
was used for 21 of the 25 use-cases, while GIS and UAV/UAS were used for 19 of the 25 use-cases each. The three technologies with the lowest range of strengths were barcodes, RFID, and e-ticketing, with results showing that barcodes were used for 4 of the 25 use cases, while RFID and e-ticketing were used for 6 and 7 of the 25 use cases respectively.

The Chi-Square test for equal likelihood was significant for GPR (p-value = 0.038, i.e., significant with 95% confidence), UAV/UAS (p-value = 0, i.e., significant with 95% confidence), and GPS/GNSS (p-value = 0, i.e., significant with 95% confidence). For GPR, the darker intensity of S-C5 indicates that DOTs that used GPR were more likely to use it for locating underground utilities and underground assets than any other selected use cases. For UAV/UAS, the darker intensity of S-C3 and S-C16 indicates that DOTs were more likely to use UAV/UAS for monitoring or determining project progress and capturing site photos and videos than other selected use cases. As for GPS/GNSS, the darker intensity of S-C12, S-C13, S-C15, S-C19, and S-C20 indicates that DOTs were more likely to use GPS/GNSS for Automated Machine Guidance, site/ROW survey, collecting as-built information and mapping of assets, earthwork inspection and quantities, and creating terrain models more than other selected use-cases.

Based on the normalized heatmap of the asset management phase (Figure 4), GPS/GNSS, GIS, and GPR were the three technologies with the widest range of strengths, with results showing that GPS/GNSS and GIS were used for 11 of the 12 use-cases each, while GPR was used for 9 of the 12 use-cases. The three technologies with the lowest range of strengths were barcodes, RFID, and e-ticketing, with results showing that e-ticketing was used for 3 of the 12 use cases, while RFID and barcodes were used for 2 of the 12 use cases each.

The Chi-Square test for equal likelihood was significant for UAV/UAS (p-value = 0.08 so significant with 90% confidence). The darker intensity of S-A6 indicates that DOTs who used UAV/UAS in the asset management phase were more likely to use it for structure inspection than any other selected use cases.

### 3.2. Results for Weaknesses

The distribution of weaknesses is represented by a normalized heat map as shown in Figure 5. For every technology, the darker the color of the weakness, the more that weakness was selected by respondents who used the technology. In terms of weaknesses, W2 (System Defects), W3 (Accessibility
for users), W4 (Integrating with current project administration systems), and W6 (Data transfer and interoperability issues) were selected for every technology at least once. On the other hand, W1 (Loss of connectivity) and W5 (Integrating with plant/supplier IT system) were not selected for GPR, while only W5 was not selected for GIS.

The Chi-Square test for equal likelihood was significant for GPS/GNSS (p-value = 0.006, i.e., significant with 95% confidence). For GPS/GNSS, the darker intensity of W1, W3, and W4 indicates that DOTs that used the technology were more likely to face these weaknesses when compared to W2, W5, and W6.

![Figure 4. Distribution of Weaknesses and results of the Chi-Square Test for equal likelihood.](image)

### 3.3. Results for Opportunities

The distribution of opportunities is represented by a normalized heat map as shown in Figure 6. For every technology, the darker the color of an opportunity, the more it was provided to the state DOTs through the technology. In terms of opportunities, O1 (Quality Improvement), O2 (Data Collection, Integration, and Management), O7 (Cost Reductions), and O9 (Decision-Making Enhancement) were selected for every technology at least once. On the other hand, O3 (Tracking Capabilities) was not selected for GPR and LiDAR, O4 (Efficiency/Productivity Enhancement) was not selected for GIS, O5 (Communication Effectiveness) was not selected for GPR, O6 (Safety Enhancement) was not selected for GIS, and O8 (Schedule Acceleration) was not selected for GPR.

Moreover, the Chi-Square test for equal likelihood was not significant for any technology. This can be attributed to opportunities being realized only after technologies reach a certain level of maturity that allows DOTs to exploit most of their potential. The higher the level of maturity, the more significant certain opportunities can become.

![Figure 5. Distribution of Opportunities and results of the Chi-Square Test for equal likelihood.](image)

### 3.4. Results for Threats

The distribution of threats is represented by a normalized heat map as shown in Figure 7. For every technology, the darker the color of a threat, the more that threat was selected by respondents who used the technology. In terms of threats, T2 (Workforce skillset limitations or resistance) and T3 (Investment costs or unknown return on investment) were selected for every technology at least once. On the other
hand, T1 (Resistance from third parties and vendors), T4 (Lack of needed support technology), T5 (Organization culture), and T6 (Policy/regulation restrictions) were not selected for GPR, while T1 and T6 were not selected for GIS, T4 and T6 were not selected for GPS/GNSS, and T6 was not selected for e-ticketing.

The Chi-Square test for equal likelihood was significant for GPS/SNSS (p-value = 0.09, i.e., significant with 90% confidence). The darker intensity of T2 indicates that state DOTs that used the technology were not likely to recognize these threats when compared to T1, T3, T4, T5, and T6.

Figure 6. Distribution of Threats among technologies and results of the Chi-Square Test for equal likelihood.

4. Discussion

The analysis of the comprehensive SWOT framework can present a holistic view of the current status quo of the state DOTs’ use of wireless and sensing technologies in highway projects as summarized in TABLE 6. This view is translated into two main forces as presented in Figure 8: the current driving forces that are pushing state DOTs to increase the use of wireless and sensing technologies, and the restraining forces that are limiting state DOTs from maximizing or exploiting the potential of these technologies in highway projects.

Starting with the driving forces, results from “strengths” and “opportunities” provide empirical evidence on the use of wireless and sensing technologies on highway projects by playing an important role in the construction phase as well as in the asset management phase. In the construction phase, technologies are allowing state DOTs to locate equipment, tools, and materials, track and document inventory, survey plots, identify underground utilities, automate equipment functionalities, conduct inspections, monitor and document project progress, and develop as-built models. In the asset management phase, the same technologies are facilitating inspection, assessing assets and their environment, identifying repair needs, and sharing information across the different departments within the state DOTs. Such use-cases of wireless and sensing technologies on highway projects – whether before, during, or after construction – are positively affecting project performance in terms of cost, schedule, safety, and quality, enhancing communication and sharing information among project stakeholders, supporting asset data management throughout the data lifecycle, and facilitating decision-making to improve processes and progress. The potential of these technologies acts as the major driver for their use, especially when state DOTs are pressured to finish complex projects under strict budgets and schedules.

Despite the major potential of wireless and sensing technologies on highway projects, state DOTs have yet to exploit or maximize this potential, and thus overcome the restricting forces. As shown in the “weaknesses” and “threats”, several limitations and obstacles need to be addressed. At the technology level, technical limitations exist in terms of connectivity, data transfer, accessibility, and effects. Such limitations are natural given that technologies continue to evolve and mature for highway projects. Additionally, the nature of highway projects which extends thousands of miles crossing rural areas, rough terrains, and tough climates provides an environment that may affect the use of wireless and sensing technologies which depend heavily on signals and connectivity. In addition to these technical limitations, obstacles are also witnessed at the level of state DOTs and their scope of work. Problems
such as resistance to change, labor shortage and lack of skills, high cost of capital investments, and non-supportive policies and regulations play a heavy role in hindering the use of wireless and sensing technologies.

Based on the SWOT findings and the status quo of wireless and sensing technologies in highway projects, the application of the technologies has proven to be an inviting and fertile ground for DOTs to invest in and implement. DOTs can address the restraining forces through different actions such as:

- Developing industry standards for the use of different wireless and sensing technologies whether at the state or federal level. This can help standardize the use of the technologies, explain their current applications, and provide a starting point to compare technology utilization among state DOTs and continuously improve this usage.

- Creating a task force and assigning champions who can lead the adoption of wireless and sensing technologies, and conduct virtual and in-person meetings dedicated to technologies, and allow state DOTs to understand maximize the technologies’ potential. Such meetings can also be critical for sharing implementation plans, best practices, and lessons learned.

- Collaborating with the contracting community to plan and execute pilot projects that can allow DOTs, contractors, sub-contractors, and other project parties to experiment with different wireless and sensing technologies freely without consequences. Such projects allow all parties to understand the pilot technology’s potential and drawbacks, draft lessons learned, and make informed decisions on whether the technology is worth rolling out.

- Collaborating with technology vendors, consultants, and research institutions. Having technology vendors available when constructing projects or conducting post-construction inspections can help vendors understand the technical issues that state DOTs face and develop solutions to solve these limitations. Consultants specialized in these technologies can also provide adequate training and conduct studies to investigate the technologies’ benefits for state DOTs and return on investments. Moreover, universities and non-academic research institutions have research labs and controlled environments to test technologies and educate state DOTs on their potential and the best way to utilize them across the project lifecycle.

- Attracting, recruiting, and retaining young graduates as they can provide state DOTs with the technical skills needed to successfully implement the technology, and play an important role in promoting the technologies across departments.

- Providing middle-level and high-level leadership support can be critical to implementing the technologies and addressing resistance to change through providing resources for pilot testing, conducting training, sharing success stories, and resolving people’s concerns.

5. Conclusion

This study presented a holistic investigation into the state DOTs’ use of wireless and sensing technologies in highway projects. A SWOT framework was developed from previous studies, and data was gathered through a nationwide survey of subject matter experts to comprehensively understand the strengths, weaknesses, opportunities, and threats of eight technologies: barcodes, RFID, e-ticketing, GPR, UAS/UAV, LiDAR, GIS, and GPS/GNSS. Analysis of the survey shows that the technologies are used in various construction and asset management use cases, providing DOTs with multiple opportunities to improve project performance and assist project stakeholders. However, technologies do face different technical, organizational, and industry-related obstacles that limit DOTs from exploiting the technologies’ maximum potential.

The findings of this study can be important for both practitioners and academicians. Practitioners can use the results to comprehensively understand the status quo of wireless and sensing technologies on highway projects. Academicians and researchers can also use the findings as a starting point to further
investigate each of the technologies to maximize their use cases and address their limitations. Findings however are based on the input of subject matter experts who answered the survey. These results reflect on the eight technologies' current state of adoption and implementation, and the experts' current experience with the technologies. Such experience is expected to change as technologies continue to evolve and mature with time, and continuous input from DOTs is needed to gain a better understanding of the potential and value of wireless and sensing technologies in highway projects.

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References


