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# Quantitative Evaluation of Advanced Traffic Management Systems using Analytic Hierarchy Process

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**Abstract**

With technological advancements in recent years, a series of intelligent transportation system (ITS) products have now become available to the transportation agencies to collect data and manage traffic conditions on the roadway network. Among ITS products, the advanced traffic management system (ATMS) has been effectively serving as the central nervous system of a traffic management center. ATMS serves as an integrated application for a wide variety of purposes ranging from data collection to implementing traffic management strategies. Owing to commercial popularity, a series of ATMS products are now available to transportation agencies and there is no consensus on selecting the best-suited product based on tailored requirements. Making a decision for a decision-critical item such as ATMS products on qualitative evidence can add risk to the decision-makers to justify their decision of choice. In this study, a multi-criteria decision analysis framework was proposed for quantitative evaluation of ATMS alternatives that can consider multiple and conflicting decision-making criteria using a real-world example. Moreover, the proposed framework was evaluated for different scenarios related to different applications of ATMS products to provide flexibility to the user in evaluating the ATMS alternatives. Results indicated that the proposed method can be considered as a viable alternative in contrast to a qualitative evidence-based decision-making strategy to minimize the risk associated with the decision-makers. Using the proposed quantitative framework, decision-makers can examine the weights of different criteria under consideration and evaluate multiple ATMS alternatives based on their jurisdiction-specific requirements. The proposed framework can be easily applied to other ITS technology selection processes.

Intelligent transportation system (ITS) is the application of technologies that make it possible to manage a transportation network more effectively. The goal of ITS in roadway transportation is to improve mobility, safety, and the productivity of a transportation system through the integrated application of advanced monitoring, communications, computer, display, and control management technologies (*1*). Under the ITS umbrella, the advanced traffic management system (ATMS) has proven to be among the most successful components in accomplishing these objectives (*2*). ATMS plays a critical role in traffic management, effectively serving as the central nervous system of a traffic management center (TMC) (*3*). The ATMS system not only communicates with all the traffic signals and roadway sensors but also helps traffic engineers monitor traffic and manage traffic signals and sensors to improve traffic flow and safety in a city.

The ATMS has rapidly gained popularity in the transportation industry because of its various applications. In recent times, a significant number of commercial vendors are developing products for transportation agencies to facilitate traffic management from a computer workstation. Because of the popularity and necessity of a central system for traffic management, multiple commercial vendors have developed their proprietary ATMS products. As a result, jurisdictions across the country have implemented ATMS products from different vendors that have been chosen to meet individual requirements. As these ATMS products contain proprietary functions and algorithms, the list features in ATMS products vary by developing vendors. However, there is no consensus available

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on how to decide which system will be the most cost-effective for a particular locality. Also, there is no established standard procedure to compare the functionalities of these ATMS from different commercial vendors. As the requirements for ATMS functionalities vary for each jurisdiction, vendors usually sell their ATMS products as core ATMS software with add-on modules to meet the specific needs of different jurisdictions. These modules, which support functions such as incident management, asset management, and adaptive signal control, are typically sold separately so that each jurisdiction can choose the modules that fit their particular needs and customize their ATMS accordingly (*4–8*). It is thus of paramount importance to have a way to understand and document the functionalities of each module from different vendors so that jurisdictions can obtain a comprehensive overview of each system and make an informed decision before they commit to a specific vendor's product.

People make decisions every day on a variety of aspects based on qualitative evidence and user preferences. In the case of choosing an ATMS product from a series of available options, a variety of features, multiple applications, and usability of available ATMS products creates a complex decision problem for the decision-makers. A unique complex decision problem also may not be applicable to different jurisdictions because of their tailored requirements for functionalities and applications in ATMS products. Moreover, deciding on qualitative evidence for an ATMS product in a transportation agency can add additional risk to the decision-makers to justify their decision of choice. Thus, a flexible quantitative framework is needed to assist transportation agencies in choosing an appropriate ATMS product.

Multi-criteria decision analysis (MCDA) is becoming increasingly popular for applications in areas such as healthcare, government, and business, where it is applied to minimize the risk assumed by the final decision-maker by guaranteeing a solution that is in accordance with the criteria in question (*9*, *10*). MCDA is a general framework for supporting complex decision-making situations with multiple and often conflicting objectives that stakeholders groups and/or decision-makers value differently (*11*). In recent years, MCDA has gained popularity in some decision-critical systems, with the most frequent application in healthcare decision-making. Several studies in the regime of transportation have also used MCDA to facilitate decision-making when working with multiple-choice possibilities (*12–17*). A review of MCDA application in the transportation field can found in a recently published study conducted by Yannis et al. (*18*). The authors noted that MCDA is mostly utilized in choosing options from series of alternatives in the transportation sector rather than for planning purposes. Guegan et al. developed an MCDA tool using the analytic hierarchy process (AHP) for prioritizing traffic calming projects (*17*). Rybarczyk and Wu used a multi-criteria evaluation analysis method to integrate both supply and demand-based criteria for bicycle facility planning (*19*). Lambert et al. implemented a scenario-based multi-criteria decision framework to assist decision-makers in effectively allocating limited resources by prioritizing transportation assets that are vulnerable to changing climate (*15*).

In the case of ITS-related product implementation projects, system engineering plays a crucial role to understand the agency requirement, adaptability, and effectiveness of ITS product for proper allocation of resources (*1*). Recognizing the potential benefit, the United States Department of Transportation requires a system engineering analysis to be conducted when procuring ITS products through a federal grant (*20*). When using state or local funding to procure ITS product, a project engineer may not need to conduct system engineering analysis because of limited resources. In such cases, a quantitative framework is needed to minimize the risk assumed by the decision-maker by guaranteeing a solution as per the criteria in question. Choosing an optimal ATMS product based on tailored requirements, multiple criteria and levels of scale need to be accounted for to make a comprehensive decision. Comparing conflicting sets of criteria when choosing the optimal ATMS product, such as functionalities and costs of ATMS products, can sometimes lead to confusion and lack of clarity. By structuring complex problems and analyzing multiple sets of criteria, informed and more justifiable decisions can be made.

Based on the above-mentioned discussion, it is evident that a quantitative framework may be beneficial to facilitate multi-criteria decision-making in choosing ATMS products for transportation agencies when using local funds for procurement. MCDA is one of the effective methods that has been implemented in decision-critical systems to choose an optimal solution from the pool of alternatives. This study focuses on developing a quantitative framework to assist transportation agencies in choosing an appropriate ATMS product based on jurisdiction-specific requirements. The objective of this study is to provide a generalized and flexible framework developed using MCDA that can guide transportation professionals in conducting a quantitative comparison among multiple ATMS products. Using the proposed framework, a transportation agency can explore multiple ATMS products within a quantitative structure, evaluate multiple and conflicting sets of criteria, and make evidence-based decisions to minimize the risk associated with the decision.

## Study Design

An ATMS product consists of a series of modules with different functionalities that are used to monitor and manage traffic operations. As the functionality and propriety algorithm varies for each product, a literature search was conducted to understand the current practice in comparing multiple ATMS products. Very limited studies were found through the literature search. The city of Hamilton developed a weighted score rating system to rank ATMS products based on information collected from commercial vendors. However, this study did not consider multiple criteria such as ATMS cost, usability, and effectiveness of ATMS functions, and so forth, when rating functionalities of an ATMS product. TransCore conducted a comparison between available ATMS alternatives under a project titled San Gabriel Valley Traffic Forum commissioned by the Los Angeles County Department of Public Works (*3*). This study subjectively evaluated different functionalities of ATMS products and prepared a comparison matrix to illustrate the benefits and limitations of each product. No quantitative rating or ranking of ATMS alternatives was conducted in this study.

As noted earlier, an ATMS product contains several modules focused on serving a specific purpose such as system detection, incident management, adaptive signal control, and so forth. Several previous studies have investigated attributes and functionalities to consider and developed a decision support system for selecting an optimal alternative for a specific module (*21–23*). Parikh and Hourdos explored the feasibility of a centralized traffic signal control system in the state of Minnesota (*22*). The authors interviewed signal operation engineers and transportation modelers across Minnesota to develop a set of intersection control information to develop an application for information sharing related to signal timing parameters. A study sponsored by the Oregon Department of Transportation surveyed traffic engineers to understand current practices and challenges related to different signal control strategies (*21*). Based on the survey responses, this study developed an Excel-based tool for selecting optimal traffic signal control strategy for a specific corridor by quantifying performance measures related to each strategy.

Based on available reports on ATMS comparison, most studies are focused on a qualitative comparison of different ATMS functionalities. A qualitative comparison of functionalities is important, but it may pose additional risk for the decision-makers to choose the most cost-effective ATMS product based on their tailored requirement. On the contrary, decision support for a specific ATMS functionality/module is highly dependent on performance measure evaluation, whereas multiple qualitative and quantitative criteria need to be considered when choosing a complete ATMS product based on tailored requirements. Thus, a quantitative framework needs to be developed to transform qualitative measures into a quantitative scale when considering multiple system requirement criteria. Another notable insight from the literature review is that both inputs from city traffic engineers and information from vendors are needed to conduct a comprehensive evaluation of ATMS products.

In the Phoenix Metropolitan Area, five ATMS products are typically used within the region. A screenshot of the user interface of each ATMS product is provided in

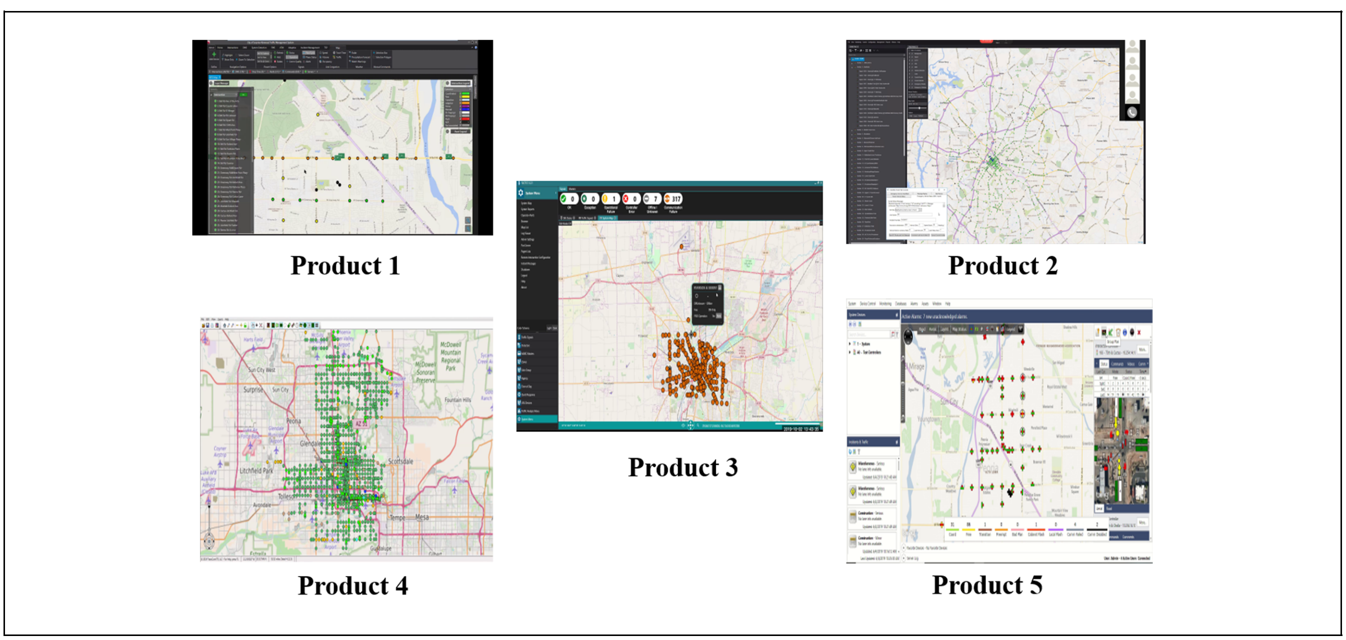


**Figure 1.** User interface of advanced traffic management system products.

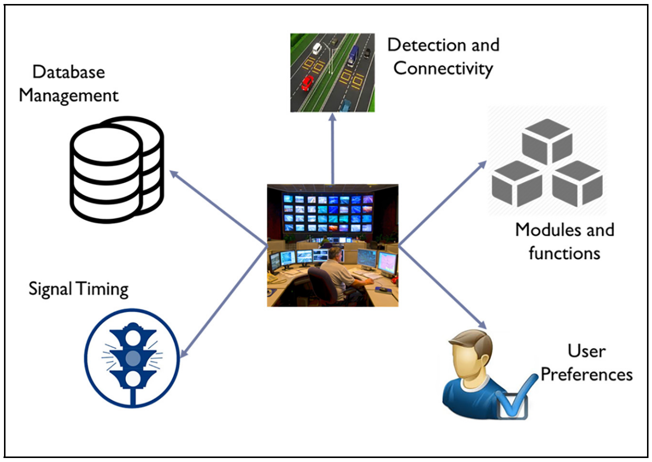


**Figure 2.** On-site traffic management center visit data collection.

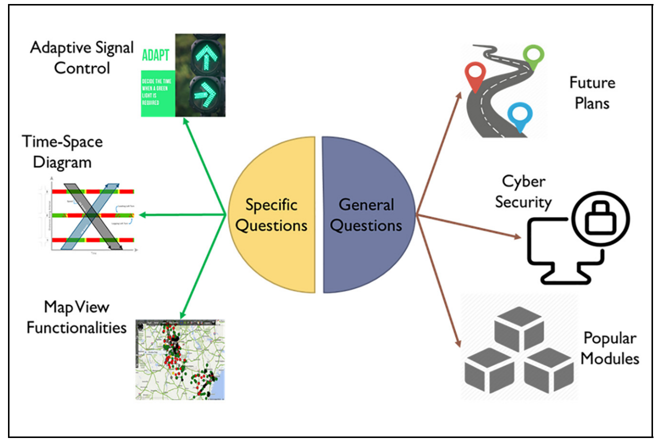


**Figure 3.** Questionnaire design for vendor interview.

Figure 1. To develop a quantitative ATMS evaluation framework for these five products, our study selected six representative jurisdictions in the Phoenix metropolitan region in Arizona. Within the Phoenix Metropolitan Area, the jurisdictions considered in this study are City of Phoenix, City of Peoria, City of Glendale, City of Mesa, City of Surprise, and City of Goodyear. Each of the six jurisdictions is currently using an ATMS product. The names of the products and the corresponding vendors are not disclosed in this study because the product names are irrelevant to the conclusions of this study. From now on, the ATMS products considered in this study will be named as System 1 to System 5 and the vendors will be mentioned as Vendor 1 to Vendor 5. Please note that the notations and sequence of products used in Figure 1 do not match with System 1 to System 5 to eliminate compliance issues. To achieve the research objectives, data was collected from two sources: (1) site visit to the TMC in six jurisdictions, and (2) interviews with the representatives from five vendors.

The site visits were conducted to gain hands-on experience on each of the ATMS products in real-world settings and collect user feedback from the software users, including the city traffic engineers who use these systems every day. The general categories of information collected during the TMC site visit in each jurisdiction are illustrated in Figure 2. Please refer to the City of Phoenix sponsored project report for more detailed information and questionnaire used to collect data during the TMC site visit to each city (*24*). User preferences play an important role in the long-term use of the software. In the context of this study, user preference mainly refers to the ease of use of each module in ATMS products and potential functionalities preferred by the users. The use of different modules and functions was observed to understand the effectiveness and usability of different functions available in each ATMS product.

It is important to note that jurisdictions using an ATMS product may not buy or utilize their chosen system to its full capacity. An interview with the representatives from each vendor of these five ATMS products considered in this study was therefore conducted to understand the full functionality of their system and their plans for the future development of these products. A list of questionnaires was developed to interview each vendor (*24*). To limit the scope of this study, the questions were developed to focus on the most used functionalities of ATMS products by the city engineers in the Phoenix metropolitan region. The questionnaire design for vendor interview is presented in Figure 3. The vendor interview questions were divided into two groups: general questions and function-specific questions. During the interviews, the vendors were asked about popular modules of their system, customer support, cybersecurity, and future plans for their products under general questions. Function-specific questions were focused on understanding the full potential of the functions mostly used by traffic engineers, such as user interface, map functionality, time–space diagram, and adaptive signal control system.

Based on information collected from site visits and vendor interviews, a list of criteria was selected that can be used in developing a quantitative framework to rank ATMS alternatives. As the ATMS products are used for a series of applications and each jurisdiction may not require all available modules in ATMS products, it would be beneficial to evaluate and rank ATMS alternatives in possible application scenarios. For example, ATMS modules for incident management and adaptive signal control may be valuable for a large-size city where the amount of traffic delay is an issue of concern for traffic engineers (*25*). On the contrary, system detection and signal control modules may be of interest for any size city (*26*). Thus, the quantitative framework needs to have flexibility so that each agency can choose its preferred criteria and evaluate ATMS systems in multiple scenarios. To account for the above-mentioned issues, a quantitative framework was developed to rank ATMS products in different scenarios. The methodology used to develop a quantitative framework and case-study application results is provided in the following sections.

## Methodology

A MCDA method is used in this study to develop a quantitative framework for comparing ATMS alternatives. One of the most commonly applied MCDA techniques is the AHP (*27–30*). This is a structured technique for organizing and analyzing complex decisions based on mathematics and psychology. The AHP, developed by Thomas L. Saaty in the 1970s, has been extensively studied and refined (*29*, *30*). The AHP represents a quantitative structured approach for quantifying the weights of multiple and often conflicting criteria. The decision-maker is required to judge the relative importance of each criterion and then specify a preference for each decision alternative under each criterion. Individual experts' experiences are utilized to estimate the relative magnitudes of factors through pairwise comparisons. The result of AHP is a prioritized ranking that indicates the overall preference of each alternative.

In pairwise comparisons between criteria, a decision-maker compares two criteria based on their importance. Most commonly, these comparisons are judged on a verbal nine-point rating scale (*27*). If criteria are judged to be equally important, both criteria are assigned a score of one. If one of the criteria is judged to be more important than the other one, the more important criterion is assigned a score from 2 up to 9, where a 2 represents a value that is *equally to moderately* more important, and 9 represents *extremely* more important. The conversion of verbal judgments from stakeholders to a numerical scale is presented in Table 1.

**Table 1.** Conversion of Verbal Judgment to Numerical Scale in Analytical Hierarchy Process

| Numerical rating | Verbal judgments |
|---|---|
| 9 | *Extremely* more important or preferred |
| 8 | *Very strongly to extremely* more important or preferred |
| 7 | *Very strongly preferred* more important or preferred |
| 6 | *Strongly to very strongly* more important or preferred |
| 5 | *Strongly preferred* more important or preferred |
| 4 | *Moderately to strongly* more important or preferred |
| 3 | *Moderately preferred* more important or preferred |
| 2 | *Equally to moderately* more important or preferred |
| 1 | *Equally preferred* more important or preferred |

Consider a decision problem consisting of I alternatives i ∈ [1, . . . , I], each need to be evaluated on J-criteria j ∈ [1, . . . , J]. The pairwise comparison matrix for J-criteria can be written as follows:

$$A = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \cdots\cdots & \frac{w_1}{w_J} \\ \frac{w_2}{w_1} & 1 & \cdots\cdots & \frac{w_2}{w_J} \\ \cdots & \cdots & \cdots\cdots & \cdots \\ \frac{w_J}{w_1} & \frac{w_J}{w_2} & \cdots\cdots & 1 \end{bmatrix} \quad (1)$$

where, $w_i$ is the converted value of verbal judgment on a numerical scale;

$$a_{ii} = 1; a_{ji} = \frac{1}{a_{ij}} \text{ and } a_{ij} \neq 0, \text{ and}$$

Based on the pairwise comparison matrix, the weight for each criterion ($W_j$) was estimated, where $0 \leq W_j \leq 1$ and $\sum_{j=1}^{J} W_j = 1$. Then, each alternative I was rated across J-criteria using the same verbal judgment scale. Let $Z_{ij}$ be the evaluation of alternative i in terms of criterion j, the utility value for an alternative I can be written as:

$$u(A_i) = \sum_{j=1}^{J} W_j Z_{ij} \quad (2)$$

where, $u(A_i)$ represents the utility value of i-th alternative.

The consistency of the judgments of the decision-makers needs to be evaluated to measure how consistent the judgments have been relative to large samples of purely random judgments. Saaty proposed to measure the consistency ratio (C.R.) to distinguish between consistent and inconsistent comparison (*28*). The basic principle behind the consistency test is that, for example, if A is preferred to B, and if B is preferred to C, then A should be preferred to C. The consistency ratio can be estimated using the following equation:

$$C.R. = \left[ {(\lambda_{max} - n)}/{(n-1)} \right] / RI \quad (3)$$

where,

$\lambda_{max}$ is the eigenvalue corresponding to the principal eigenvector,

n is the number of criteria being compared, and

RI is the Random Index, a dimensionless value that is a step function of n.

The numerator of Equation 3 can be termed as a Consistency Index. A value of C.R. less than or equal to 0.1 is considered acceptable for consistent comparison.

Although a complex decision problem can be solved using AHP, the use of multiple scenarios in the decision problem adds an additional dimension to the decision problem. Scenario planning is a contemporary temporary method like MCDA which can deal with large-scale, strategic decisions of the kind that often face uncertainties that are complex and interrelated. Ian Durbach recently published a study where the authors considered scenarios as "meta-attribute" within the AHP structure (*31*). Following the methodology proposed by Durbach, a meta-attribute AHP was applied to rank ATMS alternatives in different scenarios in this study. The meta-attribute approach suggests constructing a (k,j) scenario–attribute pairs by assigning relevant attributes in each scenario. Then, the above-mentioned AHP structure can be used to evaluate the effectiveness of each alternative in different scenarios. The global performance can also be obtained using this approach by assigning weights to each scenario and decomposing each scenario–attribute importance according to the assigned weights. The scenario-based AHP proceeded as follows (*31*):

**Step 1:** Construct (k,j) scenario-attributed pairs by assigning relevant attributes in each scenario.
**Step 2:** Construct a (k,j) x(k,j) pairwise comparison matrix based on the assigned attributes.
**Step 3:** Assess the importance of each pair of attributes based on the AHP scale. The importance of scenario–attribute pair, $\hat{w}_{jk}$ can be assessed from the pairwise evaluation where $\sum_{j=1}^{J} \hat{w}_{jk} = 1$.
**Step 4:** Evaluate each alternative i for scenario k to obtain $\hat{z}_{ijk}$.
**Step 5:** Aggregate the performance of each alternative in scenario k using $V_{ik} = \sum_{j=1}^{J} \hat{w}_{jk} \times \hat{z}_{ijk}$ from which a rank order of alternatives can be easily obtained.

## Case-Study Application

### *Problem Formulation*

Based on the methodology described in the methodology section, the problem formulation to rank ATMS alternatives using a stepwise procedure is described below:

Step 1: Define the decision problem and goal

The first step of AHP is to decompose and structure the complex decision problem: breaking the problem into smaller sub-problems makes it more manageable. In this case, we want to evaluate multiple ATMS products and rank these systems based on their effectiveness. Thus, the five ATMS alternatives were used as goals in the AHP problem.

Step 2: Identify and structure the decision alternatives and criteria

When using the AHP, the decision problem being considered is represented as a hierarchical decision structure. In this decision structure, the goal of the decision is placed at the highest hierarchical level. The first intermediate level consists of the quantitative and/or qualitative criteria that are meaningful to the decision-makers when comparing the alternatives. If necessary, each of these criteria can then be sub-divided into a cluster of sub-criteria at the next intermediate level.

Based on site visits and vendor interviews, a qualitative analysis was conducted to synthesize collected information. Inputs from traffic engineers indicated that the cost and functionalities of an ATMS product are the two major factors that usually considered when deciding on a particular system. Following similar logic, two intermediate groups were used to cluster the decision criteria in this study: ATMS Cost and ATMS Functions. The cost of an ATMS product or additional modules plays a significant role in decision-making because of the availability of limited resources to the transportation agencies. The lowest hierarchical level contains the decision alternatives, which are the finite set of alternatives that the decision-makers aim to compare. The list of criteria used in this study is presented in Table 2.

The proposed hierarchical decision structure for the AHP analysis to rank ATMS alternatives using selected criteria from two sub-groups is presented in Figure 4.

Step 3: Scenario planning

To further expand the AHP application and provide flexibility to the users, the AHP framework needs to be evaluated for various scenarios. The meta-attribute approach was used to combine relevant criteria with scenarios to generate (k, j) scenario–attribute pairs. Under the ATMS selection problem, five scenarios were selected based on inputs from the traffic engineers from study jurisdictions. The list of scenarios that was explored in this study is presented in Table 3.

Step 4: Evaluation

To compare ATMS using MCDA, a group decision approach is used. In this approach, the AHP can engage various stakeholders whose judgments on the value of alternative ATMS systems are elicited using questionnaires in a face-to-face group setting. The use of a face-to-face group setting or a real-time dispersed group setting enables the panel members to share the arguments underpinning their judgments. To provide a common ground for sharing information, it is recommended that before the group session, participants are sent an overview of the available evidence on the attributes of the alternative ATMS systems to compare. If they are to be able to value the outcomes effectively, the group members need to be informed of the existing evidence on the outcomes of the

**Table 2.** List of Criteria and Associated Sub-Groups

| Intermediate group | Criterion | Description |
|---|---|---|
| ATMS costs | Setup cost | A base cost required to purchase an ATMS with the required number of modules |
| | Operating and Maintenance cost | Annual operating and maintenance cost required to run ATMS |
| ATMS functions | User interface | A startup point from where a user can communicate with the ATMS, for example, the Startup page of an ATMS |
| | Map View | An interface where all intersections, traffic controls, and devices can be viewed |
| | Traffic Monitoring | Ability to visualize, and analyze network traffic in real-time or historically |
| | Video Surveillance | Traffic monitoring based on streaming video from cameras such as vehicle tracking, detecting abnormal traffic conditions, and so forth. |
| | Signal Priority | Ability to provide priority to transit vehicles at signalized intersections |
| | Signal Preemption | Ability to transfer of normal operation of a traffic control signal to a special control mode of operation such as emergency vehicles |
| | Split monitor | Ability to visualize traffic signal timing splits, both historic and real-time |
| | Time–space diagram | Ability to visualize green bands through a series of consecutive signalized intersections which can be used by engineers to identify coordination strategy and optimize timing plans |
| | Intersection status | Ability to detect current signal timing status, abnormality, and so forth, of intersections |
| | Alert of events | Ability to generate alert for abnormalities in traffic data, traffic controls, and devices |
| | Data Storage | Options to store data detected through traffic sensors and devices |
| | System Database | Formulation, usability, and editability of database generated by collecting data through all traffic sensors, devices, and controllers |
| | Data Visualization | Ability to visualize data in the system |
| | Report Generation | Types and numbers of reports generated automatically through the system including the ability to develop a customized report |

*Note*: ATMS = Advanced Traffic Management System.

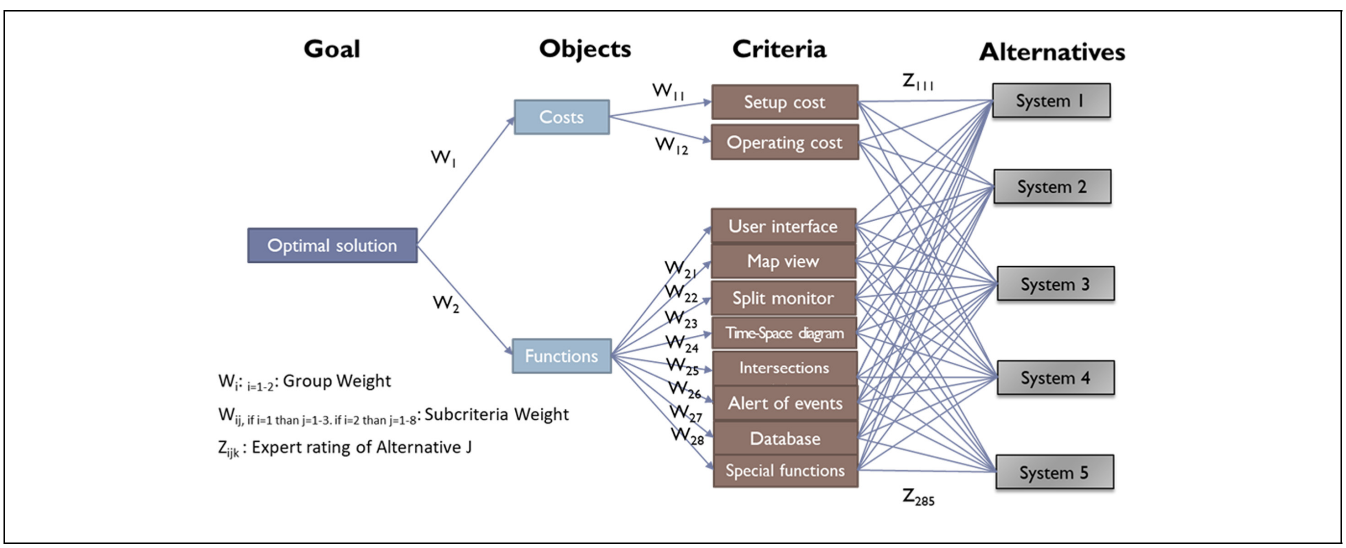


**Figure 4.** AHP structure for ATMS ranking.

new and existing systems. The judgments from the stakeholders are provided on a verbal scale, which is then converted to a numerical rating.

## Result Discussion

An expert panel consisting of senior traffic engineers employed by jurisdictions in the Phoenix Metropolitan Area was recruited to conduct a pairwise comparison between the selected set of criteria. The AHP was administered in a face-to-face group discussion setting. An Excel spreadsheet-based tool was developed to record the results of the pairwise comparisons and evaluate the ATMS products using AHP. Several worksheets were developed to conduct the MCDA using the

**Table 3.** List of Scenarios

| ID | Scenario name | Description |
|---|---|---|
| 1 | Overall Scenario | • Include all functionalities |
| 2 | System Detection | • Types and items of data collected<br>• Temporal and spatial characteristics<br>• Data visualization |
| 3 | Data Logging | • Data storage capabilities<br>• Data editing capabilities<br>• Data export capabilities |
| 4 | Incident Management | • Incident detection<br>• Alert generation<br>• Signal operation |
| 5 | Adaptive Signal Timing | • Capabilities and effectiveness of the adaptive algorithm |

**Table 4.** Pairwise Comparison Matrix of Criteria from Function Sub-Group in Overall Scenario

| Criteria | FC1 | FC2 | FC3 | FC4 | FC5 | FC6 | FC7 | FC8 | FC9 | FC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| FC1: User interface | 1 | 5 | 1/5 | 1/5 | 1/4 | 1/3 | 1/5 | 1/8 | 1/3 | 1/4 |
| FC2: Map View | 1/5 | 1 | 1/3 | 1/2 | 1/4 | 1/4 | 1/7 | 1/8 | 1/6 | 1/5 |
| FC3: Traffic Monitoring | 5 | 3 | 1 | 1 | 4 | 3 | 1/3 | 1 | 3 | 2 |
| FC4: Video Surveillance | 5 | 2 | 1 | 1 | 2 | 2 | 1/2 | 1/4 | 3 | 2 |
| FC5: Split monitor | 4 | 4 | 1/4 | 1/2 | 1 | 3 | 1/5 | 1/4 | 3 | 2 |
| FC6: Time–space diagram | 3 | 4 | 1/3 | 1/2 | 1/3 | 1 | 1/3 | 1/4 | 2 | 2 |
| FC7: Alert of events | 5 | 7 | 3 | 2 | 5 | 3 | 1 | 1/3 | 2 | 4 |
| FC8: System Database | 8 | 8 | 1 | 4 | 4 | 4 | 3 | 1 | 8 | 9 |
| FC9: Data Visualization | 3 | 6 | 1/3 | 1/3 | 1/3 | 1/2 | 1/2 | 1/8 | 1 | 2 |
| FC10:Report Generation | 4 | 5 | 1/2 | 1/2 | 1/2 | 1/2 | 1/4 | 1/9 | 1/2 | 1 |

*Note*: FC = function criteria; estimated consistency ratio = 0.095.

scenario-based problem description described in the previous section to compare the ATMS alternatives. In the case of the overall scenario, 10 out of 14 ATMS function attributes were used. Signal priority, signal preemption, intersection status, and data storage attributes were removed as the expert panel of senior traffic engineers had limited knowledge of the attributes. For all other scenarios, related functionalities were selected by the City of Phoenix traffic professionals. After converting verbal judgments from the expert panel to a numerical scale, a pairwise comparison matrix was obtained for each scenario. For brevity, the pairwise comparison matrix in the overall scenario for criteria in the Function sub-group is presented in Table 4.

The pairwise comparison matrix for sub-groups (ATMS Cost and ATMS Function), criteria in ATMS Cost were also estimated. As discussed in the problem formulation section, the pairwise comparison matrix presented in Table 4 was then normalized to estimate weights for each criterion. The weight distribution in the ATMS Function sub-group is presented in Figure 5. The visualization of weight distribution is helpful for decision-makers to verify whether appropriate weights were assigned to each decision criteria or not.

The estimated consistency ratio was 0.095, indicating an acceptable consistency in judgments from decision-makers.

It is common that if a city traffic engineer is already using an ATMS product, the ATMS rating ($Z_{ij}$) for that specific product will be biased if he or she is included in the expert panel. To remove potential bias in the quantitative framework, a separate expert panel consisting of researchers from the University of Arizona was recruited to rate ATMS alternatives for each selected criterion. The pre-requisite used for expert selection to rate ATMS alternatives was to have hands-on experience with all five ATMS alternatives considered in this study. Before rating the ATMS products, the expert panel was provided with all the documentation (ATMS synthesis report noted in Step 2 of problem formulation) related to each ATMS product considered in this study. After a thorough review and discussion, the expert panel rated each ATMS product on the criteria identified in the MCDA problem formulation. It is important to note that this expert panel had no prior knowledge of the criteria considered by the ATMS Cost sub-group. Thus, a fixed value was assigned when rating all the ATMS alternatives. The ATMS Cost sub-group was included in this

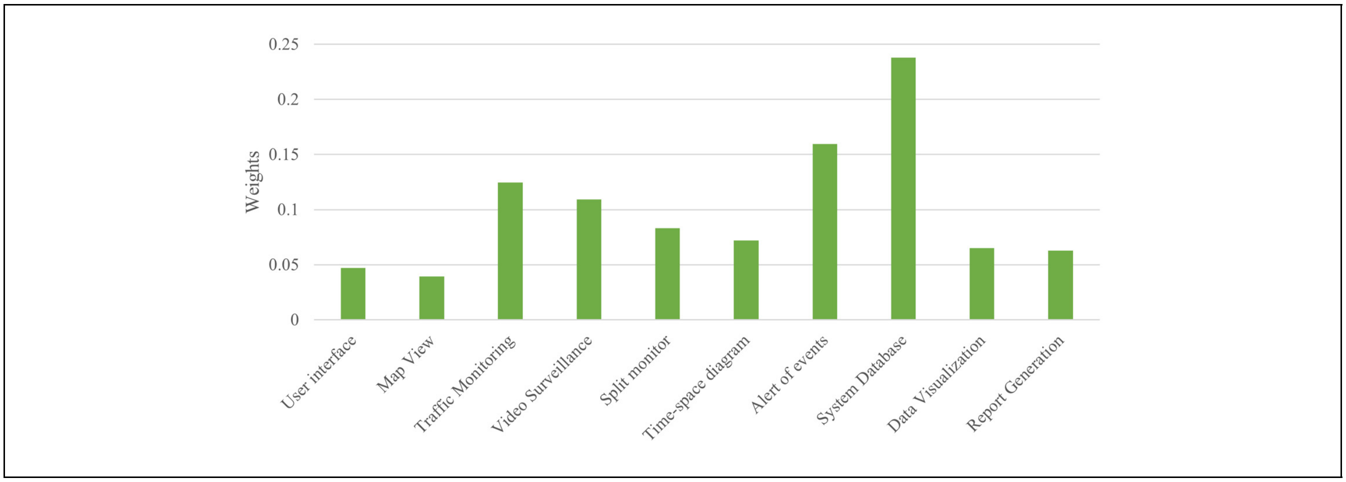


**Figure 5.** Weight distribution in advanced traffic management system function sub-group.
ATMS = advanced traffic management system

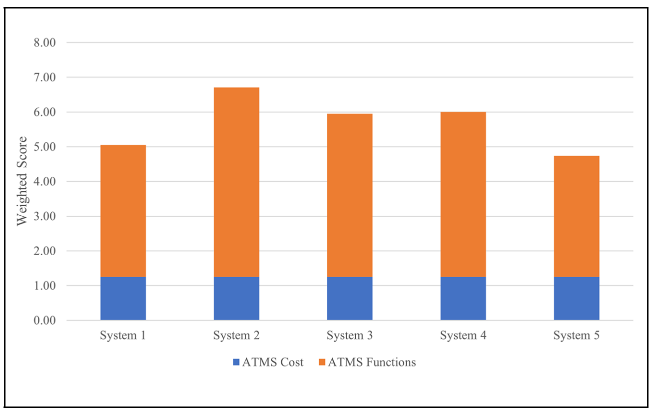


**Figure 6.** Multi-criteria decision analysis results for the overall scenario.
ATMS = advanced traffic management system

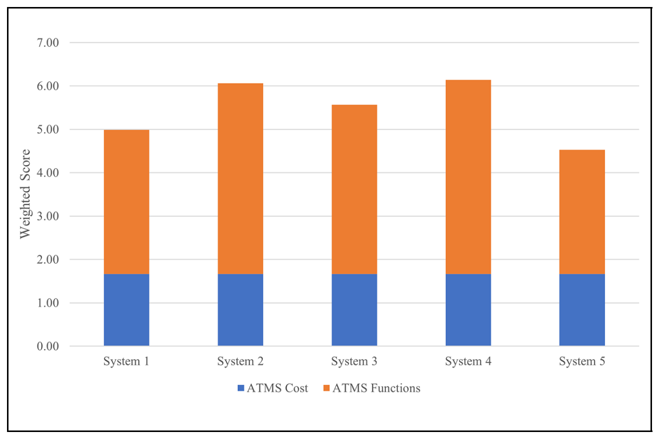


**Figure 7.** Multi-criteria decision analysis results for the system detection scenario.
ATMS = advanced traffic management system

study structure to developed a comprehensive framework for the MCDA evaluation. The Excel spreadsheet-based tool developed for this study was used to rank the ATMS alternatives and the scenario-based MCDA results for five scenarios. The MCDA results for the scenarios listed in Table 3 are provided in Figures 6 to 10.

Before discussing the results of AHP applications in different scenarios, it is worth mentioning that the MCDA results presented in this study are cost-independent. The cost of the base system or additional modules in the ATMS was not available to the study team. Only the cost of the adaptive signal control module from all five products considered in this study was available to the study team. Thus, the contribution from the ATMS Cost sub-group is constant across all five systems in Figures 6 to 9. For future implementations, any jurisdiction can easily collect relevant cost information and adjust the ratings for the ATMS Cost attributes accordingly.

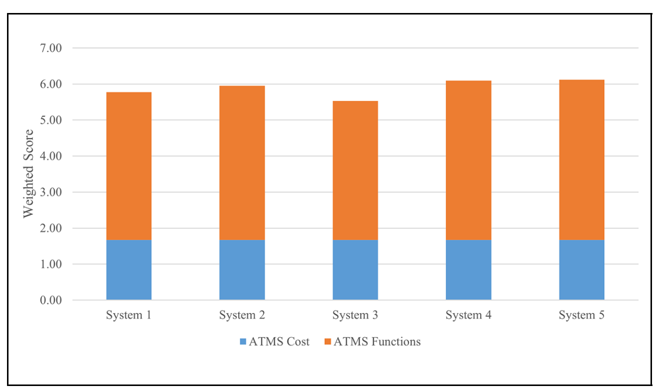


**Figure 8.** Multi-criteria decision analysis results for the data logging scenario.
ATMS = advanced traffic management system

The results presented in Figures 6 to 10 show that different ATMS alternatives were ranked top in different

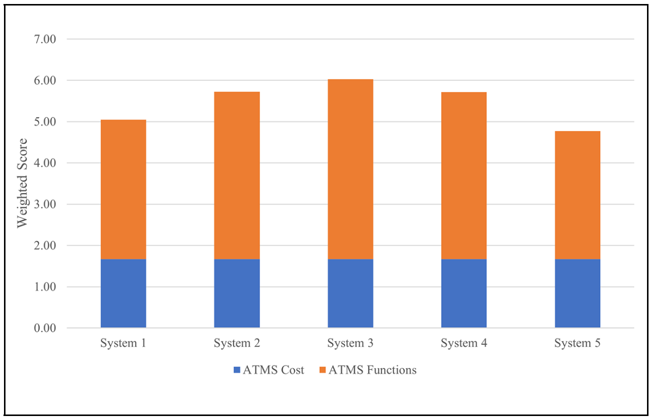


**Figure 9.** Multi-criteria decision analysis results for the incident management scenario.
ATMS = advanced traffic management system

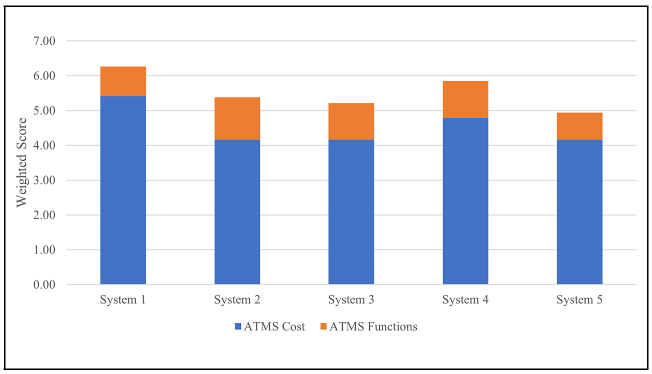


**Figure 10.** Multi-criteria decision analysis results for the adaptive signal control scenario.
ATMS = advanced traffic management system

scenarios. This finding means that no single ATMS product has the best features in terms of cost and functionality. For example, the reason why System 1 is ranked top in the adaptive signal control scenario might be that System 1 is interfaced with two adaptive signal control modules. In one of these adaptive signal control modules, a single user license is required to operate adaptive signal timing for all the intersections integrated into System 1. This feature can be beneficial in terms of cost for metropolitan areas with many signalized intersections. As noted earlier, the weight of cost features for adaptive signal control scenario was assigned a higher value by the expert panel consisting of senior traffic engineers because of the higher setup and operating cost of the adaptive module. System 3 was ranked top for the incident management scenario. In System 3, 200 built-in alerts can be configured based on the user's requirements, and these alerts can also be used to implement strategies such as changing signal timing parameters to accommodate traffic demand during an incident. In the case of the overall scenario, System 2 was ranked top among all the ATMS alternatives based on the City of Phoenix preferences and the predefined criteria. In the case of data logging, System 5 was ranked top among all the alternatives, possibly because System 5 features a new data format in their ATMS software. The vendor for System 5 is the only vendor supplying the new data format language, which is an industry-standard language that is human-readable. This new data format language can be edited using any simple text editor, giving the traffic engineer easy and full control of their configuration data.

Based on the results presented above, it can be noted that the proposed framework can evaluate multiple ATMS alternatives within a quantitative framework while considering multiple and conflicting criteria for decision-making. Thus, the proposed quantitative method should be considered as a viable alternative when evaluating a decision-critical item such as ATMS products considering the criteria in question to minimize the risk associated with the decision-makers.

## Conclusion

ATMS has proven to be the most successful component under the ITS umbrella in improving mobility, safety, and productivity of a transportation network. ATMS products contain a series of modules that create a single system for the integrated application of advanced monitoring, communication, visualization, and management strategies. As a result of commercial availability, jurisdictions across the country have implemented ATMS products from different vendors that have been chosen to meet individual requirements. However, there is no consensus available on how to decide which system will be the most cost-effective for a particular locality. Based on the existing literature review, it is evident that there is a lack of a quantitative method to help decision-makers in comparing multiple ATMS products, as making decisions on qualitative evidence can add additional risk to the decision-makers to justify their decision.

This study developed an MCDA framework for the quantitative evaluation of ATMS alternatives using AHP. Unlike point-scoring methods, AHP can incorporate qualitative factors and engineering judgments into the decision-making processing. As a case study, a real-world example of existing ATMS products currently in use within the Phoenix Metropolitan Area was used to demonstrate the effectiveness of the proposed quantitative framework. There are five ATMS products currently in use in six different jurisdictions within the Phoenix Metropolitan Area. Based on data collected through TMC site visits and vendor interviews, a list of criteria was selected from two sub-groups: ATMS Cost and ATMS Function. An expert panel consisting of senior traffic engineers employed by jurisdictions in the Phoenix Metropolitan Area was constructed to conduct a pairwise comparison between decision criteria based on collective practical knowledge and engineering judgment. To avoid bias, a separate expert panel from the University of Arizona was recruited to rank each ATMS alternatives for decision criteria. The collected verbal judgments were then converted using a numerical scale to rank ATMS alternatives. Please note that the criteria considered in each sub-group should be independent in AHP formulation. Considering highly correlated criteria within a subgroup in an AHP problem may yield biased pairwise comparison results. Thus, it is recommended to consider mutually exclusive sub-criteria in each sub-group structure in the AHP problem.

Using the meta-attribute AHP approach, a set of criteria was assigned to each scenario before the application of the AHP structure. The ranking results showed that different ATMS alternatives were ranked top in different scenarios. This finding means that no single ATMS product has the best features in terms of cost and functionality. These results suggest that no one system is superior to the others for all jurisdictions; rather, it depends on the specific applications of the ATMS product. The MCDA results presented in this study are cost-independent. The cost feature was included in the AHP structure to provide flexibility so that jurisdictions can select their list of criteria and develop scenarios based on their specific requirements to evaluate multiple ATMS alternatives using the developed spreadsheet-based tool. The MCDA results are also subjective as the attributes for each scenario were selected by the expert panel consisting of city traffic engineers based on their domain knowledge. The scenario-based MCDA ranking may change based on agency preference, modifications of ATMS ratings, and application scenarios.

The case-study implementation of the quantitative framework developed in this study was based on the limited information provided by the ATMS vendors and information collected through TMC visits. The ATMS modules from different vendors are continuously changing and evolving, the information provided by the vendors must be updated continuously over time. More information related to specific modules and functionalities can be collected in the future to conduct a comprehensive comparison between ATMS alternatives. Moreover, the application of the developed quantitative framework was applied with only jurisdictions considered in this study. The MCDA tool developed in this study can be further updated and used by multiple agencies to draw more informed conclusions. Nonetheless, the proposed framework has the potential to incorporate multiple and conflicting decision criteria in a quantitative framework. This can result in evidence-based decision-making to minimize the risk assumed by the final decision-maker by guaranteeing a solution that considers the criteria in question. Thus, the proposed method can be considered as a viable alternative for decision-making when choosing an ATMS product with tailored jurisdiction-specific requirements or deciding for an alternative for an existing ATMS product. Additionally, as the quantitative methodology was developed based on the criteria in question and multiple alternatives, this proposed framework can be transferable to other ITS technology evaluation.

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## Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Y.-J. Wu and M. Razaur Shaon; data collection: M. Razaur Shaon, X. Li and S. Ramos; analysis and interpretation of results: Y.-J. Wu and M. Razaur Shaon; draft manuscript preparation: M. Razaur Shaon, X. Li, Y.-J. Wu, and S. Ramos. All authors reviewed the results and approved the final version of the manuscript.

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