NCHRP 20-07, TASK 414

BENEFITS OF ADAPTIVE TRAFFIC CONTROL DEPLOYMENTS - A REVIEW OF EVALUATION STUDIES

Prepared for:

AASHTO Standing Committee on Highways

Prepared by:

Aleksandar Stevanovic
Nemanja Dobrota
Nikola Mitrovic

Florida Atlantic University
Boca Raton, Florida

November, 2019

Acknowledgements

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ABSTRACT

Adaptive Traffic Control Systems (ATCSs), have been in use since the late '70s but have received significant attention in the US only during the last 10 years. Since 2008, the number of these systems has increased by more than 600%. The literature review clearly shows a shortage of comprehensive studies which would gather data from numerous field evaluations, categorize those evaluations based on a number of factors (i.e., criteria), summarize findings, and develop meaningful conclusions. This study develops a framework and a tool which enables comprehensive analysis of ATCSs deployed and evaluated in the US. Compared to some previous studies, where focus was on brief and general experiences with ATCSs, this study allows a detailed analysis of ATCS deployments and investigation of numerous criteria important for ATCS deployments and evaluation. Relevant data are collected through literature reviews and surveys of deploying agencies and used to populate a database of Assessment Tool for Adaptive Traffic Control ((AT)2C). The main purpose of the (AT)2C is to help practitioners and researchers to identify, compare, assess, and monitor statistics of relevant ATCS technologies, mainly from the perspective of their field benefits achieved in field. The last sections of the report give a sample of analyses that can be performed in this direction.

SUMMARY

Adaptive Traffic Control Systems (ATCSs), have been in use since the late '70s but have not received significant attention in the US until 10 years ago. Since 2008, several surveys of ATCS deployments in the US were made but number of the deployments was very limited and thus conclusions were not based on a large sample. A project funded by National Cooperative Highway Research Program (NCHRP Synthesis of Highway Practice, Project 20-5: Synthesis Topic 40-03) in 2008, was the first attempt of comprehensive coverage of ATCSs, which also had a short overview of the ATCS's benefits. The goal of that study was to investigate domestic and foreign state of practice regarding ATCS deployments. Since 2008, the number of the ATCSs has increased by more than 600%.

Intelligent transportation systems engineers and traffic signals practitioners are very interested to find out what type of benefits (and their magnitude) can be expected from the ATCS deployments. Moreover, each deployment followed by an evaluation study needs to be more thoroughly examined to identify the factors and circumstances that lead to its success or failure. The goal of the study presented in this report is to develop a framework for extracting valuable data from ATCS deployments and evaluations. Such a framework required the data to be collected and categorized properly, followed by development of a tool that can help users to retrieve the data based on their specific goals and search criteria.

For the purpose of the data collection the research team first conducted a broad survey of the agencies which deployed and evaluated the ATCS. A number of studies collected during the literature review were used for development of framework for data categorization. Such framework was used to identify all important sections to describe the most significant conditions of ATCS deployments and evaluation studies. In addition to the literature review, a survey of the ATCS-deploying agencies was performed to collect supplemental information that was not be easily available from the ATCS evaluation studies (procurement methods, maintenance details, institutional readiness, etc.). Once all the data (according to the adopted framework for data categorization) were collected, a database was populated, and the data were available for further processing. The database was developed as an MS Excel spreadsheet which was connected to its 'front-end' – a user friendly interface developed with a purpose to provide an intuitive tool for users to retrieve relevant information. Such an integrated database, with its back-end (data table) and front-end interface (i.e. dashboards) represent essentially Assessment Tool for Adaptive Traffic Control ((AT)2C). The (AT)2C (which was updated as new data categories were added), was used to run a number of filtering processes to document some interesting ATCS-related findings.

In total, it was reported 140 ATCS deployments, out of which details were provided for 81 deployments. For the reported deployments 70 evaluation studies were conducted. However, of those 70 evaluation studies results were provided for 59 studies. It needs to be mentioned that 10 ATCSs were evaluated multiple times resulting with 14 additional studies. Interestingly, the literature review has shown that some agencies decide to evaluate ATCSs in simulation environment prior to making decision about deployment. These 12 evaluations were also reviewed and used to populate the database. In total 85 evaluation studies were populated in the database of the (AT)2C.

The findings about urban environment of the ATCSs show that 44% of the deployed ATCSs were within urban areas, 22% in suburbs, 1% in CBD and for the remaining 14% the area type was not specified. In 51% of the cases, the ATCSs were deployed on a single corridor networks, whereas 15% of the deployments were on two intersecting corridors and mixed networks. When the deployments were stratified by amount of vehicular traffic on the major corridors the findings show that around 31% of deployed systems work with AADT ranges 35,000-45,000, 22% work with AADTs between 25,000 - 35,000, 18% of ATCSs accommodate AADTs less than 25,000, and 26% of deployments work with AADTs higher than 45,000.

Based on the 36 deployed ATCSs, from which 58% are deployed in the period between 2015 and 2019, it is shown that 64% of deployed ATCSs are integrated (to some extent) with high-resolution data analyzing and reporting capabilities. In addition, 15% of deployed systems have some integration with vehicle to infrastructure technologies.

Reported average costs of ATCS installations are around $55,000 per intersection. Average costs of ATCS software licensing are around $10,000 (per intersection) and finally the average ATCS maintenance

costs, per intersection per year, are approximately $4,000. In 36% of the deployments, system engineering analysis was conducted prior to an ATCS installation. Evaluation of an ATCS was initiated in 48% by deploying ATCS agency. In 45% of the cases, the same entity that initiated evaluation study, later, conducted data collection and reported results.

Based on 85 evaluation studies entered in the database, average benefits of ATCSs can be estimated (for efficiency-based performance measures) in a range from 7.8% (number of stops) to 85% (split failure), when all evaluation periods are combined (regular (i.e., typical weekday, Mon-Thu), oversaturated traffic conditions (e.g., Friday PM peak hour) and weekend traffic). Although the range of improvements is not stellar, the results are quite consistent and they also report an increase in side-street delays for 3.4%. Similarly, transit travel times were reduced, overall, by 2.8% on average for all of the investigated periods. In terms of environmental impacts, an average fuel reduction ranged from 0.3% to 7%, whereas emission pollutants were also decreased from 0.1% to 9.8%. Finally, it was found that a number of crashes was decreased by 35.1% while an average number of conflicts was reduced by 7.6%.

When each ATCS brand was examined individually to understand benefits in achieved performance, overall findings (averaged over all time periods) show that benefits were achieved in most of the cases. However, in some instances ATCSs failed to outperform previous type of control. Since each evaluation represents a specific case, readers are encouraged to investigate specific cases of their interests by using the (AT)2C and relevant referenced studies.

Investigation of various AADT levels, as a proxy of overall traffic congestion, has shown that higher benefits were achieved on networks with moderate traffic (i.e., AADT is between 35,000 and 55,000) than on those with high traffic (AADT higher than 55,000). This is the case for all of the efficiency-based performance measures. However, when ATCSs deployed on the roads with relatively low AADTs (i.e., less than 35,000) are compared with those from any other AADT group (i.e., moderate, high), the results are not consistent. In terms of impact of signal retiming frequency of the pre-ATCS signals, it was found that higher benefits (for all periods considered) were achieved for moderately frequently retimed signals than for very frequently retimed signals. When results from relatively rarely retimed signals were compared with other retiming frequencies, results were not consistent to draw a meaningful conclusion.

When different pre-ATCS signal control types were analyzed, it was found that benefits from evaluated ATCSs tends to be higher when ATCSs are installed on networks previously controlled by semi-actuated signals than if fully-actuated signals were present. When benefits of ATCS deployments were correlated to the urbanization of the network, the observed results were consistent. ATCSs deployed in suburban environments reported improvement in all efficiency-related performance measures. Similarly, the same trend was observed for systems deployed in urban areas with one exception, side-street delay was increased by 6.2% (for all periods averaged).

For the most dominant network type, which is a single corridor, covered by the evaluation studies, efficiency performance measures were improved anywhere between 2.8% (transit travel time) and 85.5% (split failure), averaged over all time periods. Only delay side-streets was worsened by 6.3%. In cases when ATCSs were deployed on two intersecting corridors, for all combined periods, it was found that delay and number of stops were increased by 7.1% and 24.6%, respectively, although, other performance measures were improved (e.g. network-based travel time by 5.4%). In the case of mixed networks over all combined periods, findings show that ATCSs were capable of improving all efficiency-based performance measures between 5.1% (side street delay) and 40.9% (network-based number of stops). However, these results were not consistent in terms of environmental-impact performances.

When compared to some of the previous studies, where focus was given to overall experiences of the ATCS agencies, this study allows researchers to step into details (as recorded in the database) of each ATCS deployment/evaluation and investigate numerous criteria. On the other hand, considering that such a large number of criteria required a time-consuming data entry process for agencies' representatives, a relatively low survey response rate was achieved. In addition, not all of the data categories (answers) were reported for all of the ATCS deployments. Some of the reasons for this omission could be the length of survey, lack of the knowledge to provide relevant answers, lack of the relevant data, etc.

Limitations of this study are mainly related to the data collection methods. In the first place, a small response rate from agency representative's prevented collection of a large data sample to develop a robust database. In some cases, agency's staff (who possess proper knowledge) was not available during the survey's open window, which impacted the quality of the feedback received. On the other hand, when the relevant data are collected only through the literature review, it was impossible to get all of the required information from the available data.

Future research should be directed in periodical maintenance of the database by entering new data entries. Findings show that several ATCS deployments within the last five years integrated some elements of the emerging technologies. It is expected that this trend will continue in the following years; thus, it is of particular importance to monitor how these applications will be affecting ATCSs and their management and operations.

C H A P T E R   1   B A C K G R O U N D

Introduction

Adaptive Traffic Control Systems (ATCSs), have been in use since the late '70s but have received significant attention in the US only in the last 10 years. Until 2008 several surveys of ATCS deployments in the US were found in literature, but their scope was limited and thus the conclusions were unsupported by data from large sample. A project funded by National Cooperative Highway Research Program (NCHRP Synthesis of Highway Practice, Project 20-5: Synthesis Topic 40-03) in 2008, was the first true attempt of comprehensive surveying of ATCSs with a limited coverage of their benefits. The goal of that study was to address domestic and foreign state of practice on deployment of the ATCSs. At that time only around 40 agencies in the US operated a single ATCS, and each of those deployments were usually followed with a field evaluation study. Since 2008, the number of these systems has increased by more than 600%. There are several factors contributing to this rapid ATCS growth: ATCS was promoted as an effective tool for combating day-to-day and special event- traffic flow fluctuations, successful deployments (based on evaluation studies) encouraged many other agencies to deploy these systems, and finally emergence of new ATCSs brands which were more user friendly than the old ones. Emergence of these new ATCS brands (sometimes referred as 'plug-and-play ATCSs'), accompanied with good promotions and marketing, help to skyrocket ATCS deployments within the last 10 years.

Based on periodical communication with ATCSs vendors an author of this study maintains a database-map (https://goo.gl/2CSQnE) that contains existing ATCSs deployments, which is updated annually or biannually. Figure 1 shows ATCSs deployments around US based on a 2018 survey. There are currently more than 350 ATCSs deployments in the US and Canada. However, there are still many questions that remained unanswered about operational and safety benefits of these systems. It is noteworthy that not every deployment is followed by systematic and periodic evaluations which would document continuous benefits from the ATCSs. Some agencies prefer to conduct in-house monitoring and evaluations of the system. Reason for this shortage of documented evaluation studies may lay also in budgetary constraints.

Intelligent Transportation Systems engineers and traffic signals practitioners are very interested to find out what type of benefits (and their magnitude) can be expected from ATCS deployments. Moreover, each deployment, followed by an evaluation study, needs to be more thoroughly examined to identify which of the factors and circumstances lead to its success or failure. In the cases where an ATCS deployment was not successful (and the system was decommissioned (partially or fully)), examination of causes that lead to system decommissioning can result in a very valuable lesson to learn for future deployments. It is of special interest to identify all of these factors for each ATCS deployment and evaluation, and present them in coherent and consistent framework.
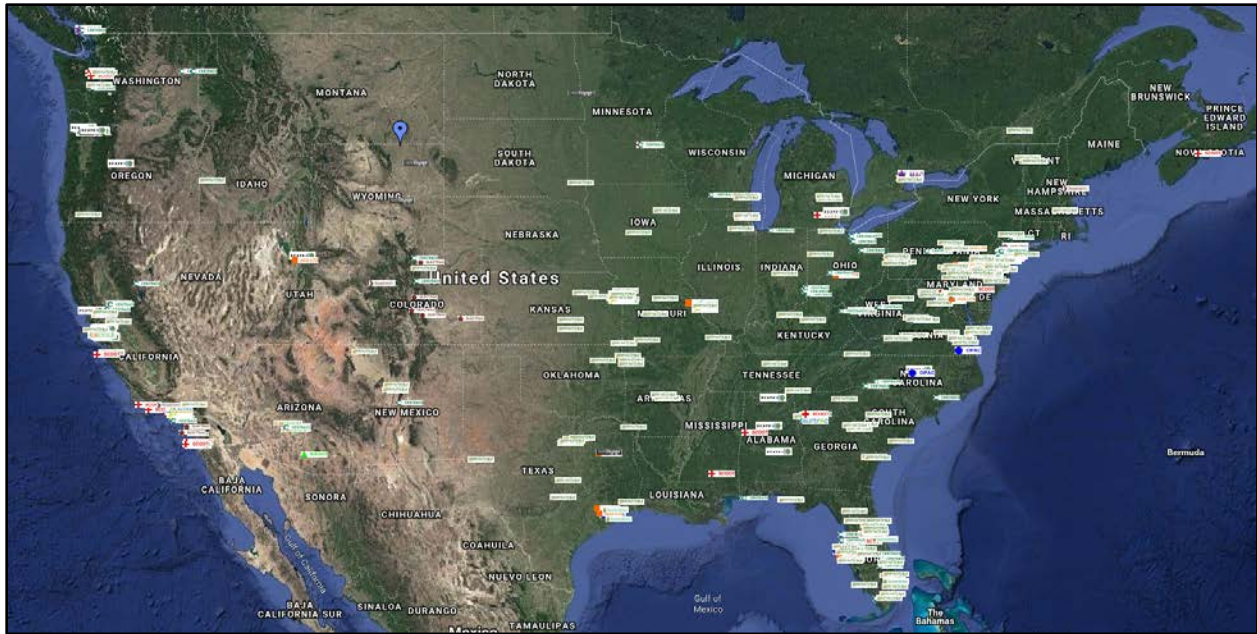
Figure 1 Map of ATCS deployments around the US

[Source: https://goo.gl/2CSQnE]

Literature review

With rapidly increasing number of deployments, within last couple of years, federal, state and local agencies followed ATCSs installations with respectable number of publications (i.e., guidelines, recommendations, tools, evaluation studies, etc.) addressing various aspects of this technology deployment.

Popularity of ATCSs in the US was recognized around 10 years ago, when number of deploying ATCSs started to increase. In order to capture and provide better understanding of these systems around same time two studies that relayed mainly on surveying of deploying ATCSs agencies were conducted (Selinger and Schmidt (2009), Stevanovic (2010)). In their study Selinger and Schmidt (2009), investigated three main aspects of an ATCS, installation costs, maintenance and reliability of system. The survey was distributed to the 38 agency representative from which 34 participated. Follow-up study (Selinger and Schmidt (2010)) was conducted in order to assess some new ATCSs technologies that had rapid deployment at that time and to cover operational benefits resulting from these systems deployments.

First comprehensive attempt to cover deploying ATCSs trends within US and worldwide was done by Stevanovic (2010). In a synthesis report, by surveying deploying ATCSs agencies the author documented all major aspects of ATCSs covering, deploying environment, working principles, institutional aspects, system requirements, costs and benefits of ATCSs. Survey was delivered to 42 agencies in the US where 34 participated in the survey, in addition, 11 agencies aboard were surveyed. Based on literature review Fehon and Peters (2010) and Zhao and Tian (2012) provided an overview of a major ATCSs in the US.

In the following years, Lodes and Benekohal (2013) conducted survey of deploying ATCSs agencies in order to evaluate the costs and safety benefits of implementing ASCT technology in the United States. It was noted that ATCSs lead to crash reduction however, sample size was too small for statistical testing. Out of 62 deploying ATCSs agencies, 22 participated in the survey, however, only 17 of them reported information further processed.

Above mentioned studies served as a good source of information regarding ATCS technology. However, guidance for practitioners which can be seen in the still unanswered questions remained. Some of these questions are: Should an agency consider ATCS? Which network warrants ATCS deployments? Which

benefits can be expected from such deployment? Which ATCS brand should be deployed? What is the best way to assess benefits of deployed ATCS? Large group of authors tried to answer to some or all of these questions using various scientific approaches. In the following, the authors listed some of the most important studies.

From the perspective of system engineering analysis, Fehon et al. (2012), developed an extensive guidance for the agencies to guide their representatives through the process of developing systems engineering documents for assessment and selection of an ATCS. This guidance document is feasible tool to examine current agency conditions (i.e., jurisdictional, financial, operational, etc.), assess whether or not ATCS is likely to address anticipated network issues and to decide what type of adaptive control is appropriate for agency.

Identifying a network which is suitable for ATCS deployment was recognized in the past by many researchers (Mudigonda et al. 2008, Wang et al. 2013, Studer et al. 2015, Ban et al. 2016, Sharma et al. 2018). In some of these studies in addition to identification of suitable ATCS network, recommendations on which particular ATCS brand should be deployed are given.

In their work Mudigonda et al. (2008), developed GIS-based decision support system tool combining macroscopic simulator and a rule-based expert system in order to provide decision of whether OPAC, SCOOT, SCATS should be implemented on a particular network. Decision making process was based on obtaining best benefit-cost (i.e., b-c) ratio if particular system is deployed.

Wang et al. (2013), developed a tool capable of indicating the suitability of a particular traffic control strategy, non-adaptive (i.e., fixed or actuated) or adaptive traffic control for a given network. Survey of literature and practicing professionals was undertaken to determine current state of the practice regarding both control types. The authors developed methodology framework which is implemented in a Microsoft Excel-based tool which assists practitioners in selecting when and which systems to evaluate. Although study aimed to make uniform approach for not easy achievable 'fair' ATCSs comparisons, study was conducted in the jurisdictional boundaries of Oregon Department of Transportation where current practice was focused on three adaptive traffic control systems (i.e., InSync, ACS-Lite and SCATS).

In a comparative analysis of four ATCSs (i.e., SCATS, SCOOT, InSync and UTOPIA) Studer et al. (2015) based on evaluation studies, documented benefits from each system deployments, among its costs and some limitations of each system. Main goal of this study was to provide governments and authorities guidance on which ATCSs should be most appropriate for deploying in desired networks. Main limitation of study is lack of details about each deployment/evaluation as well as number of evaluated systems.

Ban et al. (2016), developed a decision-making tool for practitioners in order to guide them whether or not adaptive control should be deployed on particular corridor. Tool is composed from two components, decision tree for qualitative analysis and regression models and support vector machine (SVM) for quantitative analysis. Decision tree was based on current nation state of practice while regression models and SVM rely on large amount of data from various sources. Proposed approach was applied on one arterial corridor where it was found that proposed quantitative methods lead to different conclusions. Further improvement of tool was recommended by authors.

In a more recent study Sharma et al. (2018) developed methodology to monitor and compare arterial corridors in terms of mobility-based performance measures. This process alleviates selection of corridors with existing need for retiming and in addition to identify corridors suited for ATCSs implantation.

Need for more analytically driven rather than intuitive decision in the process of selecting the optimal ATCS for procurement was addressed in the work of Mladenovic et al. (2015). In the form of decision support tool starting from functional requirements, transportation agency need to develop technical requirements followed by decision-making criteria for ATCS evaluation. Set of functional requirements is listed and necessary to consider for particular location by the agency before any further action is made.

Within the Every Day Counts initiative, FHWA recognized that ATCSs have not been deployed widely mainly for two reasons, cost and complexity of system on one side and lack of clear benefits documentation on the other. In an attempt to overcome lack of evaluation studies comprehensiveness, Gettman et al. (2013), developed generic measures of effectiveness and evaluation tools to validate how deployed ATCSs meet

agencies performance objective. Case study in Mesa, Arizona, was conducted in order to validate proposed approach.

Extensive ATCSs simulation modeling on particular network in order to provide answer which system to deploy was done by Zhao and Tian (2011). They examined SCATS and ACS Lite systems simulated within VISSIM and CORSIM simulation software packages. Number of different traffic conditions were simulated in order to assess which system performs better on given network.

In one comprehensive evaluation study done by Fontaine et al. (2015), evaluation of 13 InSync pilot deployments throughout the Virginia State was conducted. Aim of this study was to investigate benefit-cost ratio of these pilot deployments by conducting evaluation. The finding from the pilot tests were used to identify key considerations for future sites and overall favorable benefit-cost ratio was estimated.

Relatively large number of the evaluation studies conducted by consulting agencies, in-house or even research institutes, and universities are usually performed for one or two deployed ATCSs. Such studies, used for the population of the database are listed and presented in Appendix A of this report.

This literature review showed that although many groups of authors proposed viable methods in determination of which system and on which network should be deployed, many aspects of deploying an ATCS were overseen that can be used in the process of decision making for ATCS deployment. For instance, deploying ATCS agency environment (i.e., agency jurisdiction, budget limitations, workforce, etc.), operational ATCS environment (i.e., pre-ATCS traffic control type, frequency of pre-ATCS signals fine tuning, AADT on the busiest corridor where ATCS is deployed, etc.), evaluation environment (i.e., entity who initiated evaluation study, entity that conducted evaluation study, evaluation method and type, etc.). In addition, studies which serves to propose particular ATCS brand are mainly due to complexity of testing and simulating various systems, limited with number of ATCSs brands that are proposed. In one attempt based on real life deployments and evaluation studies within US, this report summarizes all major factors important for an ATCS deployment and evaluation. In addition, beside conclusions generally derived from obtained data in this report (through surveying deploying ATCSs and literature review), each individual can perform their analysis to learn more about deploying/evaluating environment and to assess to which level (based on conducted evaluation) benefits from such deployments are achieved using Assessment Tool For Adaptive Traffic Control (AT)2C.

Objectives and scope

The goal of this research is to develop guidance for practitioners on evaluating, selecting, implementing, and maintaining ATCSs. The guidance should identify successful practices in ATCS application, systems integration, maintenance, and monitoring for the deployments in the US. An intuitive tool is provided in order to help practitioners assess performance and make objective-based decisions for appropriate implementation.

This goal has been achieved through the following objectives:

- Developing a methodology to categorize data from ATCS evaluations (Creating a framework for data categorization of ATCS evaluations)
- Gathering information regarding ATCS deployments and evaluation studies
- Creating and populating database with collected data
- Developing database-driven intuitive tool for data filtering and information retrieval

Report organization

This report consists of seven chapters. In first chapter problem background and research objectives are presented. Following chapter provides research approach used in this study, with short description of each activities within this research. Chapter three summarizes development of appropriate methodology for data categorization regarding ATCS evaluations. This methodology represents a framework where all criteria (categories) of interest were addressed. In the chapter four, data collection method, in particular surveying efforts, were documented. Chapter five describes how database and tool for data filtering and information retrieval are developed. Main components of the tool are described in this chapter. Chapter six provides a number of filtered data examples extracted from the developed tool. Number of interesting queries, cross-referencing various types of data, are presented in graphical and tabular forms to document some interesting facts about ATCS deployments and evaluations. Finally, chapter seven summarizes the information presented in the previous chapters and offers conclusions that might help agencies interested in deployments of particular ATCS systems. Separate lists of references and acronyms precede five appendices. Appendix A contains list of evaluation studies used for population of the database. Appendix B presents framework for data categorization with corresponding definitions of categories, reasons for consideration in framework, and similar. Appendix C contains the survey delivered to deploying ATCS agencies. Appendix D provides list of surveyed agencies (within the US and Canada) who deployed ATCSs. Appendix E contains a manual that describes how to use the (AT)2C.

CHAPTER 2 RESEARCH APPROACH

Introduction

This research was conducted in a sequential manner, i.e. where each task follows a previous one as shown in Figure 2. However, since the data collection lasted during the entire course of the study some of the project tasks were conducted in an iterative manner (i.e., defining new categories for data filtering). Research approach shown in Figure 2 are briefly explained in following sections. Figure 2 also shows alignment of different project tasks and the chapters of this report, so that a reader knows in which chapter to expect coverage of certain tasks.

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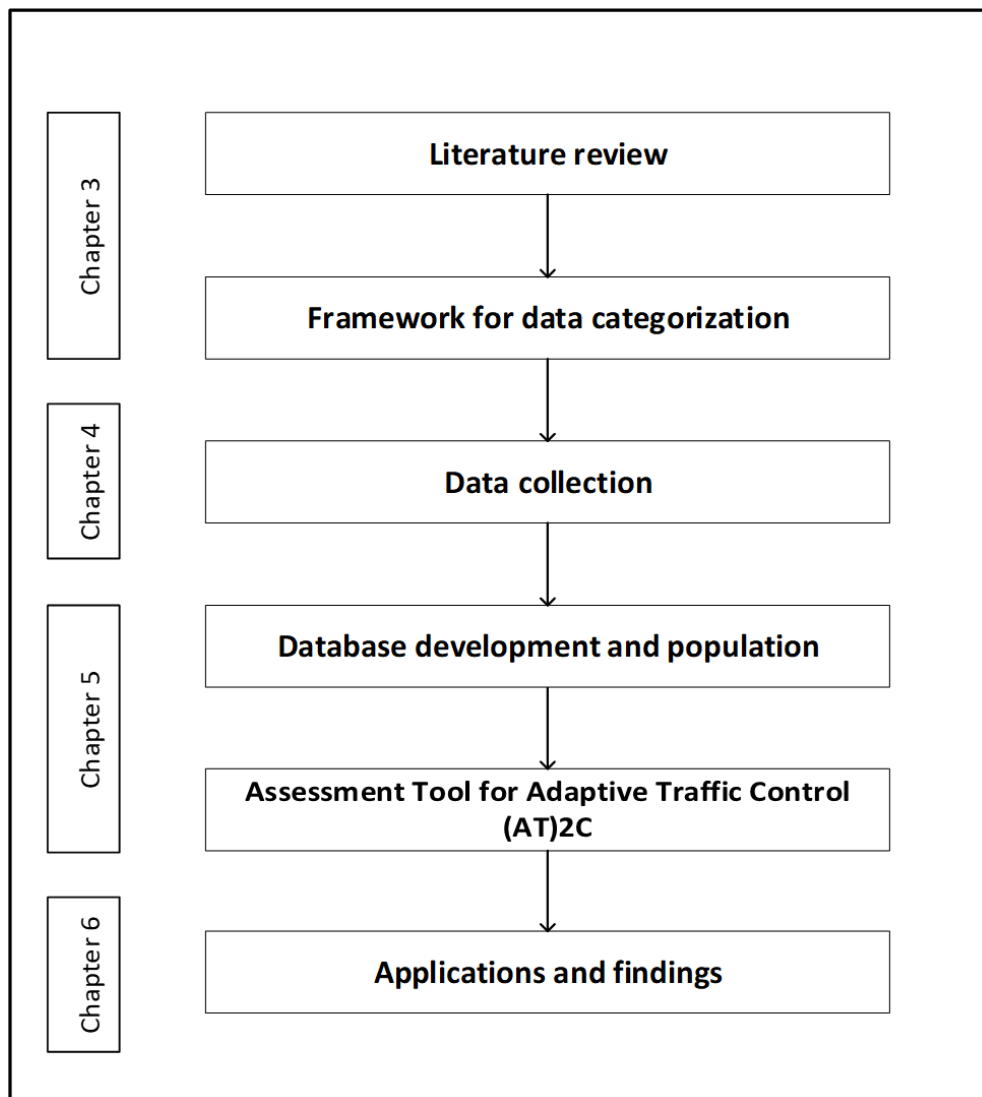
Figure 2 Research approach and task alignment with the chapters

Literature review

In order to develop guidance on selecting, implementing, maintaining, and evaluating an ATCS, literature review was conducted as an initial research activity. Relevant studies which were available online were

downloaded and classified based on many categories and keywords. Some of these initial data categories were used later for the development of framework for filtering categorization.

Framework for data categorization

Studies collected during the literature review were used for development of framework for data categorization. Such framework was used to identify all important sections to describe the most important conditions of ATCS deployments and evaluation studies. The number (and coverage) of the selected categories was determined to be large enough to cover all major aspects of ATCS evaluations but also small enough to make the querying and filtering processes manageable and intuitive.

Data collection

While a good quantity of necessary data was obtained through the literature review it was needed to collect additional data through the other methods i.e. by surveying agencies who have deployed ATCSs. In addition, one of the purposes for the survey was to get supplemental information that may not be easily available from the ATCS evaluation studies. For example, while operational benefits of a particular ATCS deployment may be obtained from a before-and-after evaluation study (e.g. a document available online), institutional aspects of the deployment (procurement methods, maintenance details, institutional readiness, etc.) may not be available unless the agency is asked directly in a survey/phone call or similar.

Database development and population

Once all of the data (according to the adopted framework for data categorization) were collected in previous research activities a database was populated with these data. This database was developed as an MS Excel spreadsheet where each column represents a single data attribute (i.e., category) and each row contains an ATCS record instance (i.e., deployment/evaluation study).

Assessment Tool for Adaptive Traffic Control (AT)2C

A populated database in the previous step was then connected to its 'front-end' – a user friendly interface developed with a purpose to provide an intuitive tool for users to retrieve relevant information. Such an integrated database, with its back-end (data table) and front-end interface (i.e. dashboards) represent the Assessment Tool for Adaptive Traffic Control ((AT)2C tool). The (AT)2C is developed as a standalone tool—within MS Excel—which contains multiple dashboard pages, each with a number of visual aids (i.e., graphs, charts, and tables) and elements (i.e., slicers, and time-line slicers) which provide users options to conduct data filtering and retrieval. In addition, the (AT)2C is accompanied with a short user manual— found in Appendix E—describing how to use the (AT)2C.

Data analysis and reporting

Once the (AT) 2C was developed (and updated as new data categories were added), it was used to run a number of filtering processes to document some interesting ATCS-related findings. Summaries of such findings are presented in the Chapter 6—Applications and findings.

CHAPTER 3 FRAMEWORK FOR DATA CATEGORIZATION

Framework overview

Based on the literature review of evaluation studies, and other related materials, it is possible to categorize the data of interest regarding relevant ATCS deployments and evaluations. Most of the evaluation studies are retrieved from online sources by using a number of keywords such as *ATCS, ATCS evaluations, ATCS deployments, ATCS performance assessment, etc.* Each evaluation study (and evaluated ATCS) is specific due to numerous factors such as, operational conditions, agency's institutional circumstances, layout of the road network, etc. For example, a small agency which wants their ATCS to address significant variations in seasonal traffic, on an arterial street in suburban area, with a specific emphasis on side-street delays and level of service, will benefit very little from learning how an ATCS performs in a downtown grid network under jurisdiction of a very large agency, whose predominant operational objective is to balance private traffic with multimodal operations.

Thus, the goal of this task is to develop a data categorization framework which will help users to find out (i.e., filter out) relevant ATCS deployment/evaluation cases for their interests. For this reason, the framework significantly relies on a proper definition of relevant fields, categories, and sub-categories that can be used as filter out appropriate case studies and data from a database representing a 'library' of the existing ATCS evaluation studies. These data categories are presented in a coherent way so that filtering of the ATCS evaluation studies can be done in a proper manner.

The framework for data categorization of ATCS evaluations consists of four identified areas (annotated as Sections A-D, as shown in Figure 3), where each section contains a number of categories and sub-categories.
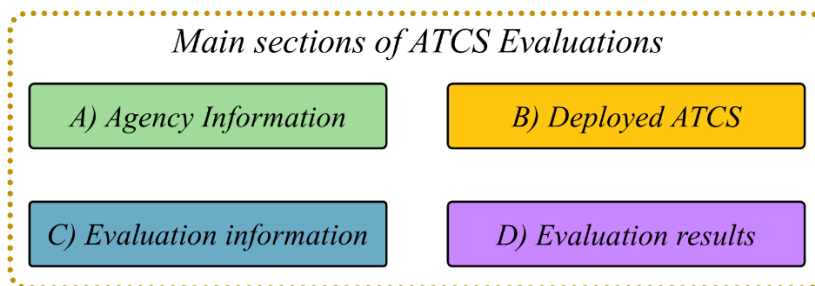
Figure 3 Main sections regarding ATCS Evaluations

Section A – Agency details

Section A contains most of the relevant information about a particular agency, its institutional aspects, and similar. There are four main categories which were identified as important aspects which influence deployment and operations of an ATCS. These categories are related to basic agency's information, its jurisdiction and workforce, and budgeting. Within these four categories, following sub-categories were identified as shown in Figure 4.
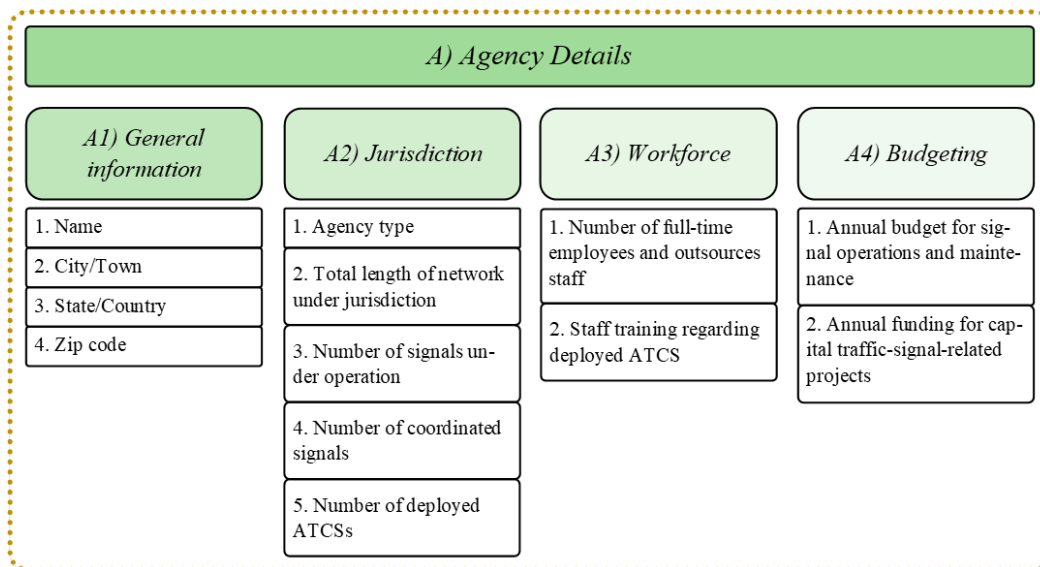
Figure 4 Categories and sub-categories within section A

Following represent the most relevant questions that are addressed within this framework:
1. What is covered within each category/sub-category?
2. Why a particular category should be included in the framework?
3. How will the data for such categories be obtained?
4. How will the collected data, in the proposed framework, be utilized?

We provide detailed answers to these questions in the Appendix B. For the question # 1, a brief definition of each category/sub-category is provided. To address the question # 2, we discuss importance of a particular category/sub-category in agency's decision-making process. For the question # 3, we explain whether the relevant data are collected through a questionnaire and/or from other relevant evaluation studies.

Prior to addressing the question # 4, we should remind readers that two major outcomes of this project are: (i) development of database-driven intuitive tool for data filtering and information retrieval and (ii) final report, which will document all of the research efforts including the objectives, research approach, findings, conclusions, and recommendations for future research. Thus, most of the collected data will be utilized to address one or both of these two objectives. For example, a user of the database-driven tool, the (AT)2C, will filter out relevant ATCS evaluation results based on sub-categories such as, A2-1 Agency type, A2-3 Number of signals under operation etc. However, some of less-intuitive sub-categories (e.g., A3-2 Staff training regarding deployed ATCS) may play a more important role in the final report than for filtering processes.

Section B – Details of deployed ATCSs

The Section B examines data categories related to deployed ATCSs. Eight major categories are identified to examine various perspectives of deployed ATCS:
1. Deployed ATCSs and monitoring
2. Selection method and installation of the ATCS
3. Area coverage of the ATCS
4. Objectives and operational environment of the ATCS
5. Communications and detection of the ATCS
6. Previously utilized traffic control system

7. Capital and maintenance costs of the ATCS
8. System monitoring and operations

For reach identified category multiple sub-categories are developed to acknowledge important factors related to particular ATCS deployments. Such data categories and sub-categories are shown in Figure 5. In addition, Appendix B contains further details about definitions, justification for selection, and explanations of these data categories and sub-categories.

B) Details of Deployed ATCSs

B1) Selection method and Installation of ATCS	B2) About area where ATCS is deployed	B3) Area coverage of the ATCS	B4) Objectives and operational environment	B5) Communications and detection of the ATCS	B6) Previous traffic control system	B7) Capital and maintenance costs	B8) System monitoring and operating
1. ATCS selection method	1. City	1. Network type	1. Main reason(s) for ATCS implementation	1. Transmission media	1. Previous type of traffic signal operations	1. Average costs of installation per intersection	1. How understandable are working principles of deployed ATCS?
2. Installation timeline	2. Zip code	2. Urban area type	2. ATCS performance assessment	2. Detection layout	2. Previous control type on ATCS deployed corridor/network	2. Costs of installation of ATCS software	2. Which signal timing parameters can be adjusted in real time?
3. Installation issues	3. City population	3. Length of covered network	3. ATCS multimodal environment	3. Detection technology	3. When was the last time when signals were retimed on the subject network?	3. Average maintenance costs of ATCS per year	3. Expected ATCS life cycle
4. Status of deployed ATCS	4. Metropolitan Area	4. Number of signals	4. ATCS integration with emerging technologies		4. Previous signals fine-tuning frequency		
5. Who was involved in process of decision making?	5. Metropolitan area population	5. AADT					

Figure 5 Categories and sub-categories within section B

Section C – Evaluation information

The Section C examines data categories related to the processes of evaluating deployed ATSCs. For the Section C, three main categories are identified; which are then further expanded in sub-categories as shown in Figure 6. For each ATCS deployment, data for these sub-categories will be collected, which will establish a basis for a fair comparison of evaluation results (see Section D) in the (AT)2C.
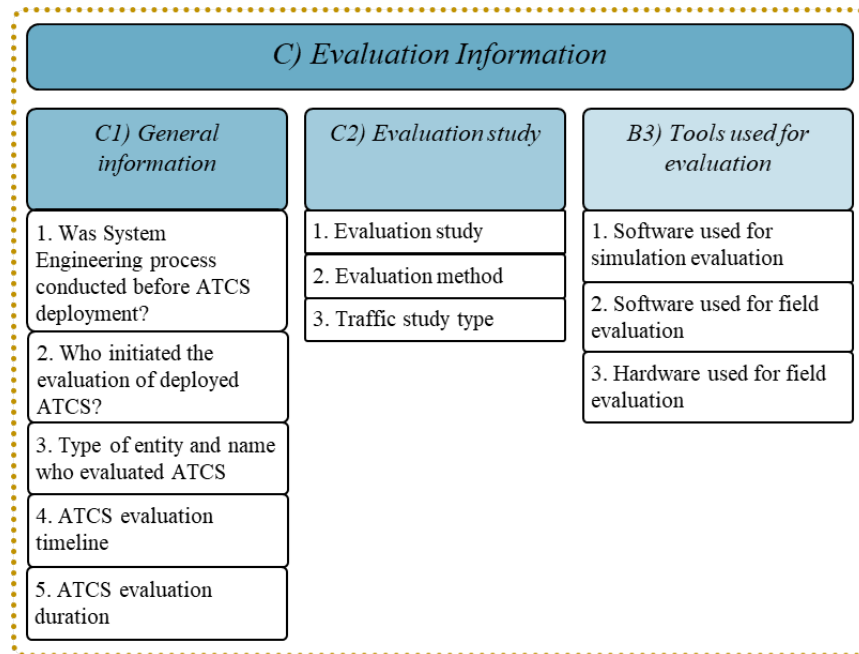
Figure 6 Categories and sub-categories within section C

Detailed explanation of all categories and sub-categories, their justifications for selection, and means of data collection are presented in Appendix B.

Section D – Benefits of deployed ATCSs

The Section D covers the data categories related to the evaluation results (e.g. benefits) of the ATCS deployments. Three major data evaluation categories in this section are related to weekdays, special traffic events, and weekends. The weekday results are grouped in three distinctive peak periods (AM, Mid-day, and PM). On the other hand, the special events, illustrated through the oversaturated conditions, are usually associated with incident or sport events in the influenced area. In most of the cases these are either Friday's PM peak hours or peak hours on any other day when the traffic demand is higher than during typical weekdays. In addition, some of the studies investigated lighter traffic demand that is present usually during weekend days. Finally, some evaluation studies reported overall benefits throughout a weekday (not for peak periods separately).

Within each of these categories, additional sub-categories are established, representing common performance measures used to evaluate ATCS deployments (shown in Figure 7). It should be noted that the database allows future extension to add new performance measures based on some new high-resolution data.

Figure 7 Categories and sub-categories within section D

CHAPTER 4 DATA COLLECTION

Development of the survey

The purpose of the survey was to get supplemental information that may not be easily available from the ATCS evaluation studies. For example, while operational benefits of a particular ATCS deployment may be obtained from a before-and-after evaluation study (e.g. documented in an online report), institutional aspects of the deployment (agency profile, institutional readiness, etc.) may not be documented in any of the available sources. Thus, a survey was developed to inquiry about such data elements for all of the agencies which have deployed ATCSs (in the last few decades) in the North America.

The original idea was that the survey will be used to collect data in accordance with the categories/subcategories presented in the framework for data categorization of ATCS evaluations. However, data for some of the subcategories were collected later upon receiving survey responds. The reason for this was to reduce the burden put on the surveyed agencies whose time for filling the survey may be limited. Examples of such subcategories are populations of the agency's city, population of the corresponding metropolitan area, and similar.

The survey consisted of open-ended, multiple-choice, multiple-answer, and file-upload questions. Moreover, the survey was developed in such a way where some answers triggered additional questions (e.g., if a respondent used simulation to conduct ATCS evaluation another question would pop up asking about type of simulation tool). In this way the survey was adapted to serve multitude of users with various characteristics. Also, depending on the number of the ATCSs deployed and evaluated, a survey participant was required to repeat the portion of survey related to benefits of evaluation. Naturally, if an agency deployed multiple ATCSs, evaluations could have been done for each specific deployment. In such cases, when an agency would need to enter information multiple times, it was ensured that entries about general information of the agency are not unnecessarily repeated. In addition, during filling of the survey, participants were given options to upload evaluation studies/reports, where applicable. This was beneficial in cases where a single agency conducted multiple evaluation studies, in which case a burden of filling necessary information is transferred from the surveyed agency to the surveyor (FAU research team). In such a case, a participant was given a chance to simply upload an evaluation report/study which was examined by the FAU research team once upon receiving the survey response.

A sample of the survey is included in the Appendix C. It should be noted that questions 1-10 are related to agency's capabilities, management, and budgeting. Questions 11-62 are about deployment process and the process of evaluating ATCS' performances, and finally questions from 63 and above are about outcomes of the ATCS evaluations. One should note that questions in the last group, are triggered based on the comprehensiveness of the time periods which are considered during the evaluation process. For example, if the evaluation was conducted only for weekday AM and PM peak hours, on single corridor, only two questions (e.g. 63 and 65) would appear. However, if the evaluation was done for more time intervals (e.g. mid-day), the other questions may appear as well.

Identification and participation of the relevant agencies

An initial list of agencies (that have deployed particular ATCSs) was developed based on the reviewed evaluation studies during the literature review process. By surveying these agencies, the idea was to populate the database with the missing information (e.g. profiles of the agencies and other circumstances of the ATCS deployment processes). In addition to the literature review following sources were used to expand the list of agencies invited to participate in the survey:

- Previous synthesis study on various ATCSs in the USA and Canada (NCHRP Synthesis of Highway Practice, Project 20-5: Synthesis Topic 40-03) served as a source which provided a list of 34 agencies within and outside US (i.e. Canada).

- Furthermore, the most comprehensive list of ATCS deployments in the US was developed by principle investigator (i.e. Aleksandar Stevanovic) through annual communication with ATCS vendors to update the map of ATCS deployments (https://goo.gl/2CSQnE).
- Finally, some of the ATCS vendors' websites were visited to retrieve information about any recent ATCS deployments.

From all of the above sources, a list of the agencies to survey was developed and this list is presented in the Appendix D. However, during the process of the literature review it was noted that some other studies (not highly relevant for adaptive traffic control but relevant to the traffic signal operations and management) may also be used as a good resource to survey traffic signal agencies across the US. One of such studies was the 2018 Traffic Signal Benchmarking Self-Assessment (commissioned by the National Operations Center of Excellence), whose recipients were also added to the previously formed list.

In total, the list of identified agencies contained 349 agencies in the USA and 11 agencies in Canada. The original survey was developed in online form, by using one of the most common online surveying platform (i.e. SurveyMonkey). A pilot version of the survey was delivered to a few agency representatives, whose suggestions and comments were incorporated in the final form of the survey. The final (official) form of survey was delivered to more than 500 email addresses (of the municipal, county, and state agencies) in the United States and Canada on February 22nd, 2019. In total 35 responses were recorded from corresponding state, county or city agencies, whose states are shown in Figure 8.
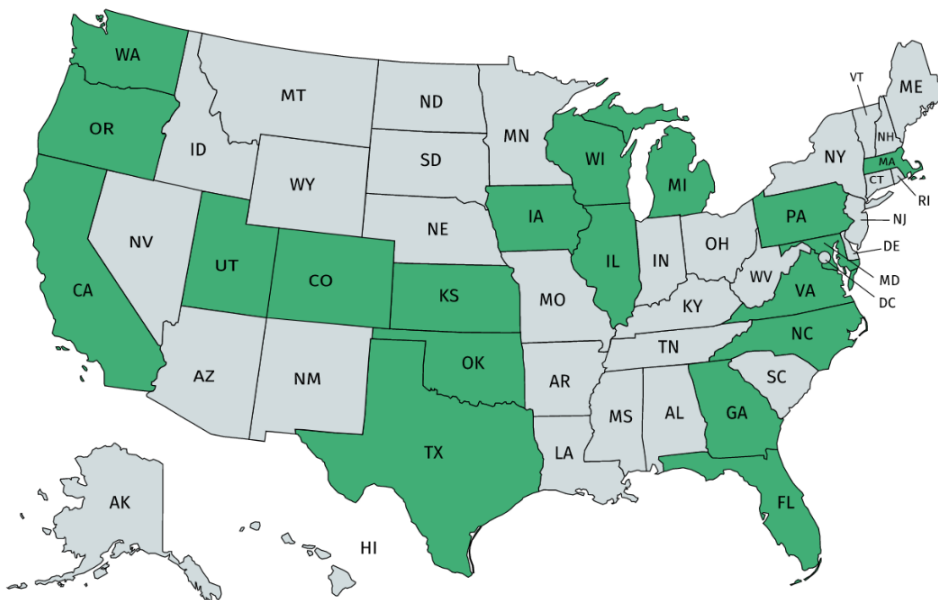
Figure 8 States with agencies which participated in the survey

CHAPTER 5 ASSESMENT TOOL FOR ADAPTIVE TRAFFIC CONTROL – (AT)2C

Introduction

This chapter provides an overview of the development of database and user interface of Assessment Tool for Adaptive Traffic Control, i.e. (AT)2C. The (AT)2C is developed with the main purpose to help practitioners and researchers in the identification, comparison, assessment, maintenance, and monitoring of the ATCS technologies. The (AT)2C is envisioned as a standalone tool (developed within MS Excel), which is intuitive and relatively easy to use.

Development and population of the (AT)2C database

Data gathered through the literature review and survey were used to populate the database. The database was developed in a MS Excel spreadsheet. The Excel framework allowed enough flexibility (e.g. enough columns and rows to cover the needs) that the outcome has validated the decision to use the MS Excel. The database is designed in such a way where each column represents a category from the data categorization framework. However, a limitation of this approach was that it was necessary to use an additional column for every attribute that a particular data category could contain. For example, in the case of ATCS detection technology we needed to assign one column for each type of such technology (e.g. inductive loops, video detection). Also, each ATCS deployment/evaluation was labeled as a single record instance in the database, as illustrated in Figure 9.

Record Instance	1. Name of Agency	2. City/Town	3. State/Province	4. Zip Code	5. Country	6. Agency type	7. Cumulative length of the road network	7.1 Cumulative length of the road network	8. Number of signalized intersections under operation	8.1 Number of signalized intersections under operation	9. Number of coordinated signals under operation	9.1 Number of coordinated signals under operation
1	Maryland DOT State Highway Administration	Hanover	MD	21076	United States	State governme	>2,400 miles	17178	>500	3500	>300	1571
2	Missouri Department of Transportation – Sou	Jefferson City	MO	65102	United States	State governme	>2,400 miles	33853	>500	2616	>300	1190
3	West Goshen Township	West Chester	PA	19380	United States	City government	<200 miles		<100		<50	
4	FDOT – Miami	Miami	FL	33172	United States	State governme	200-800 miles		<100	47	<50	30
5	CDOT	Greeley	CO	80634	United States	State governme	800-1,200 miles		100-200		50-80	
6	City of Renton	Renton	WA	98057-3232	United States	City government			100-200			
7	City of Austin	Austin	TX	78754	United States	City government	>2,400 miles		>500		984	>300

SECTION A
A1 - Basic Agency Information

Figure 9 Structure of the database

So far there are 107 recorded ATCS instances in the database. All of the records from surveyed agencies which stated that they do not operate ATCSs were excluded from the study. However, there are few agencies which have deployed ATCSs but have not evaluated them yet. Such responses were kept in the database for two reasons: first, it is beneficial to investigate deploying ATCS environment even when an evaluation study was not conducted; and second, in the case that relevant evaluation study is performed in future, results of such evaluation could be easily appended to a record that will already exist in the database.

Overview of the (AT) 2C

The (AT) 2C provides two types of analysis: (1) analysis of the operational and institutional environment where the ATCS is deployed; and (2) analysis of reported benefits from the ATCS deployment. These analyses are performed by filtering data through the selection of appropriate categorized data, entered for each ATCS deployment/evaluation. In the first case, the (AT)2C can be used as a dashboard whereas in the second case its primary role is to serve as a filtering tool. The (AT)2C is accompanied with a short user manual, which describes how to use the (AT)2C.

Each of (AT)2C's sections contains several components which are common for all of its sections: (1) heading, (2) research overview, (3) navigation buttons, (4) slicers for filtering and (5) visualization of the filtered data. Such a layout from (AT)2C is shown in Figure 10.
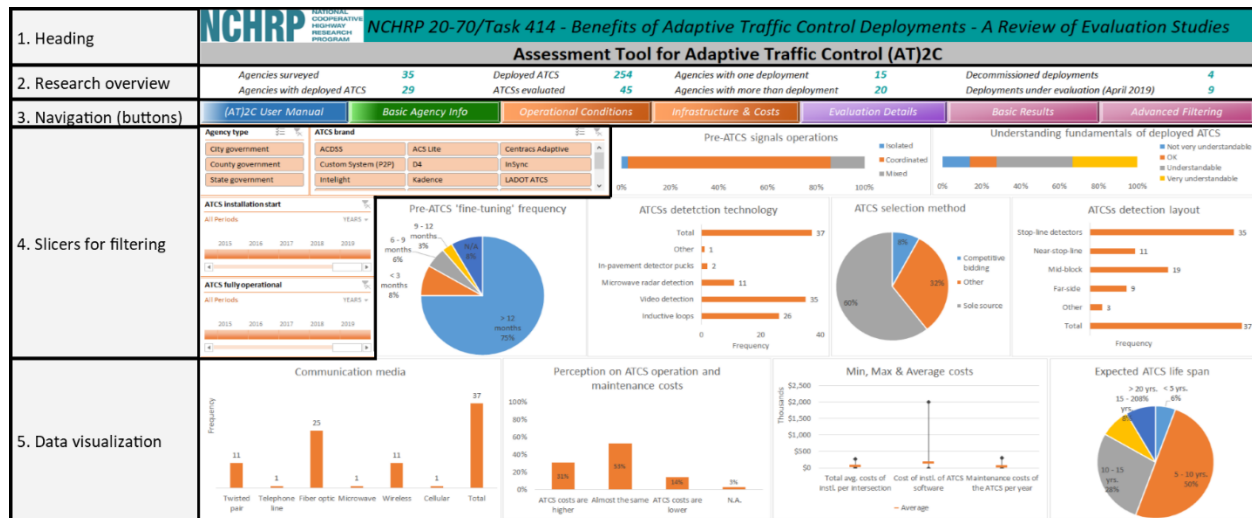
Figure 10 (AT)2C dashboards and components of the filtering tool

(AT)2C – Dashboard

This (AT)2C section represents a set of interactive dashboards where a user can conduct analysis of ATCS operational conditions based on categorized data, after filtering is done with slicers and similar tools. Each dashboard page contains a number of visuals (i.e. graphs) whose purpose is to illustrate data selected through user's filtering actions. Four dashboard pages are created to cover (AT)2C dashboard's functionalities:

1. Basic Agency Info.
2. Operational Conditions
3. Infrastructure & Costs
4. Evaluation Details

The Basic Agency Info. covers organizational and institutional context of the agency which deployed given ATCS technology (e.g., number of employees, organizational structure of agency, preventive maintenance/operational budget etc.). This page also covers details of the installation process (e.g., installation delays, potential decommissioning and installation reasons and stakeholder coordination). A user can filter the data based on several criteria, such as, agency type, deploying state, installation timeline, etc.

By selecting a filtering category/criterion, a user initiates a process where relevant data are retrieved from the database and visualized on the predefined charts, tables, and other visualization aids. Charts and tables are updated automatically based on the filtering selections. If no selection is made, the visualization aids will display given performance measures and statistics based on all of the records in the database (as shown in Figure 11).

Figure 11 Basic agency information (Dashboard Page 1)

The Operational Conditions page can be observed through a number of factors, such as: system conditions (number of signals under operations, prevailing AADT of the main corridor(s), area and network type coverage), system monitoring and control, integration of existing infrastructure with new and emerging technologies, multimodal operations, and alignment of agency's objectives with the ATCS' technology.

Analysis within this dashboard page can be performed through a selection of particular ATCS brands where for each selection visual aids are updated. In the case that no selection is made, visualizations are based on all of the records in the database (as shown in Figure 12).

Figure 12 Operational conditions of ATCS deployment (Dashboard Page 2)

The Infrastructure & Costs page covers a number of relevant criteria, such as, ATCSs detection technology and layout, communication infrastructure between central hardware/software and field traffic controllers; pre-ATCS signal operations and fine-tuning frequency; associated costs of operating ATC systems; and an expected ATCS life-span. In the case that no filtering/selection is made, this dashboard page shows the statistics based on all of the databases' records, as presented in Figure 13.

Figure 13 Infrastructure & costs (Dashboard Page 3)

In order to provide better understanding of evaluation benefits of deployed ATCS, a dashboard page entitled Evaluation Details was developed. This page covers mostly information based on the three main data categories: evaluated ATCS brand, evaluation entity, and evaluation timeline. Visual aids are based on the main evaluation criteria, which address questions such as: Who initiated a ATCSs evaluation study? Which entity conducted the ATCS evaluation? What evaluation method was used? What study types were used? and What hardware and software were instrumental for the evaluation(s)? This dashboard page, when no filtering selection is made, is presented in Figure 14.

Figure 14 Evaluation details (Dashboard Page 4)

(AT)2C – Filtering tool

This (AT)2C section allows a user to perform more comprehensive analysis of the data (as opposed to relying on the visualizations predefined by the abovementioned dashboard pages). A goal of such analysis is to investigate benefits, captured by various performance measures, from deployed ATCS. The filtering part of the (AT)2C contains two pages:

1.   Basic Results
2.   Advanced Filtering

The filtering functionalities of the (AT)2C allow a user to run analyses based by using either predefined selections (Basic Results) or more customized selections (Advanced Filtering). As an output, a user gets benefits of various performance measures reported for different time periods (e.g. TODs) in the evaluation studies. Moreover, for each performance measure, a user can retrieve information about which record number in the database corresponds to a particular evaluation. This record number can later be used to identify an agency that installed and evaluated the system and similar.

Within the Basic Results page a user can investigate benefits of deploying a particular system. Analysis is based on several criteria such as, agency type, urban area type, network type (where the ATCS is deployed), type of pre-ATCS signal operations, number of signals under ATCS, etc.
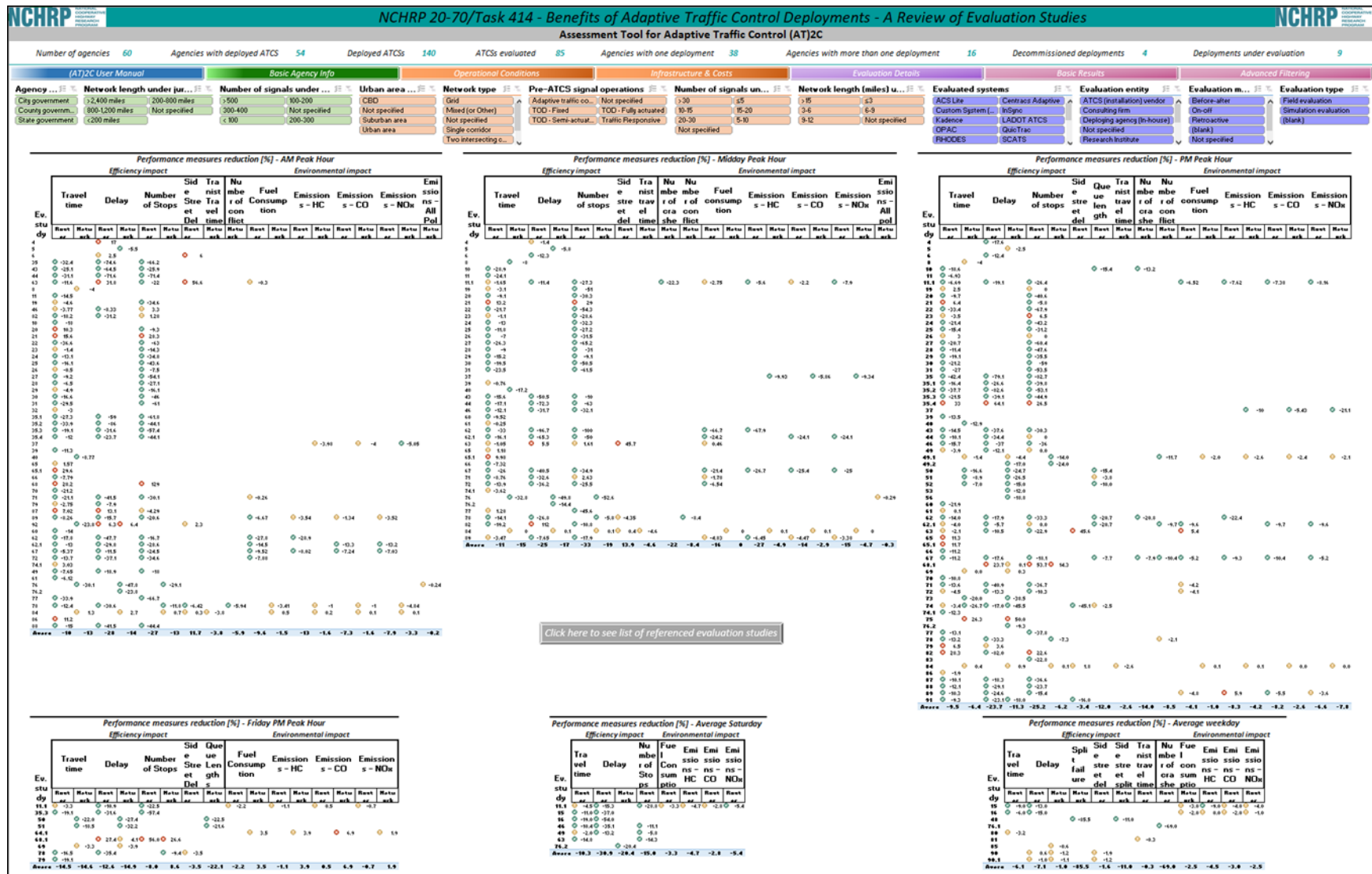
Figure 15 Basic evaluation results

Under the Advanced Filtering, a user can obtain the same type of results as under the Basic Results page but he/she has much more flexibility to apply numerous filtering options. The main screen of this page is presented in Figure 16.
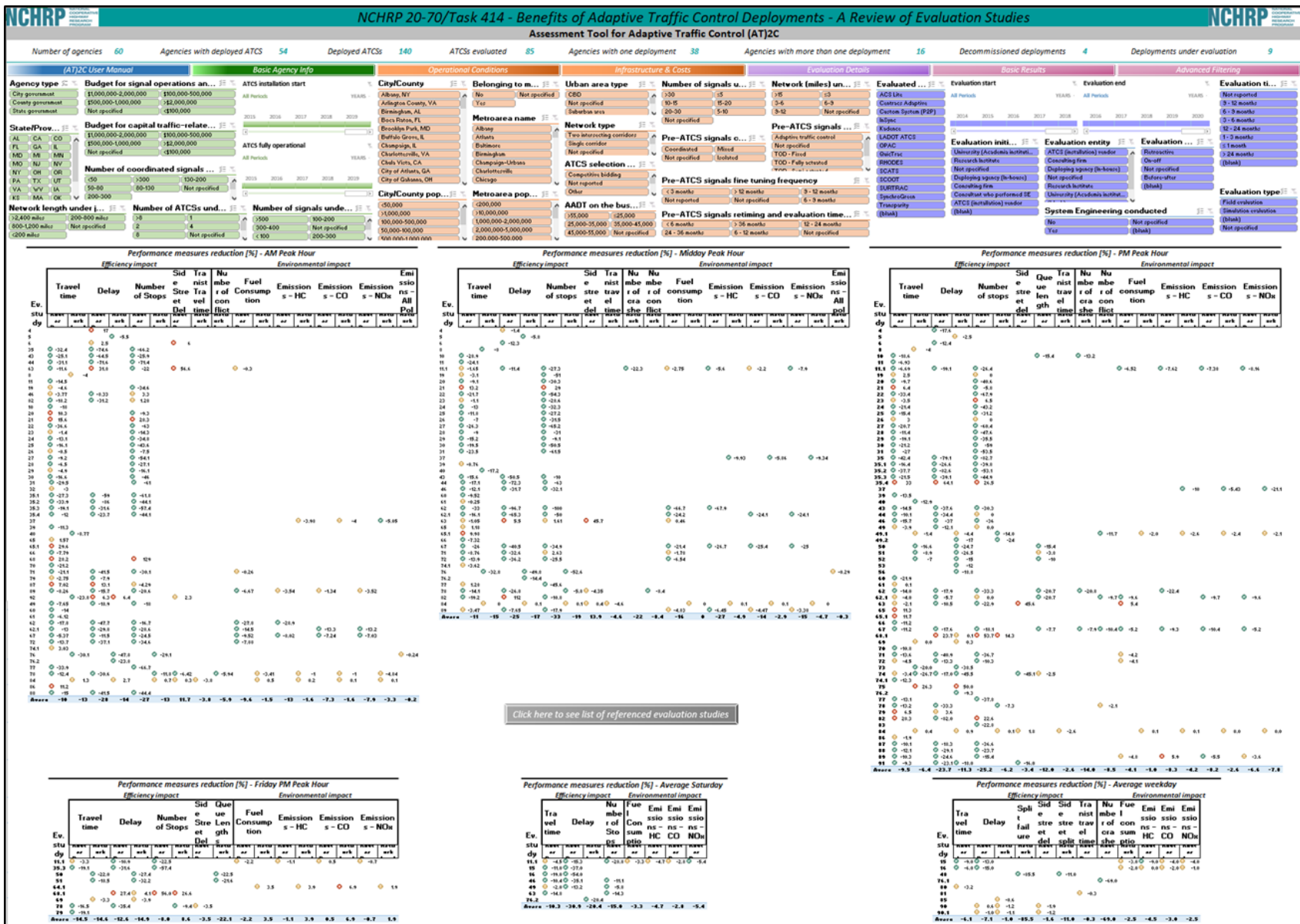
Figure 16 Advanced filtering option

CHAPTER 6 APPLICATIONS AND FINDINGS

Purpose of this chapter is to present a sample of findings when the (AT)2C is used to retrieve the information about ATCS deployments and their effectiveness. Thus, this chapter contains a summary of collected and cross-referenced data about the collected ATCSs deployments. The chapter is organized in following manner: survey summary results are presented first, followed by a series of data summaries addressing institutional and operational aspects, infrastructure and costs, and evaluation environment. The chapter is closed with some cross-referencing insights and conclusions.

Survey results

The survey of the ATCS-deploying agencies was delivered to 349 agencies in the US and 11 in Canada. Of those only 35 agencies responded to the survey, out of which 6 agencies responded that they have not deployed any ATCSs yet. Considering that the project was scoped to analyze only those agencies who have experiences with the ATCS those 6 agencies were excluded from further consideration. In total 29 responses from agencies that have deployed ATCSs were analyzed. Distribution of responses per agency type is presented in Table 1.

Table 1 Number of participating agencies, per type, in survey

Agency type	Number of participating agencies
City government	16
County government	4
State government	9
Total	29

All of the responding agencies are US-based. There were in total 140 deployed ATC systems. These systems are distributed, per type of deploying agency, as shown in Table 2.

Table 2 Number of deployed ATCSs per agency type

Agency type	Deployed ATCSs
City government	56
County government	14
State government	70
Total	140

Distribution of deployed ATCSs, per an ATCS brand, is presented in Table 3. For each deployment (and each evaluation, separately) it was necessary to highlight both a reported number of deployed/evaluated systems and the data populated for each deployment/evaluation. This was needed because a single agency deploying ATCSs could have more than one system. Further, an ATCS deployment could be evaluated multiple times. Table 3 shows this difference as the second column reports a total number of deployments, but the third column shows if such a deployment is entered in the database (e.g. an agency could report and existing deployment but the data are not entered). Similarly, the fourth column shows how many evaluations have been conducted but the fifth column shows if the results for such evaluations are reported in the database. Several agencies reported multiple deployments of ATCSs within an agency without providing more details about each deployment and ATCS brand, such answers were grouped under 'Not specified' brand in Table 3.

Table 3 Success rates to obtain information about deployed and evaluated ATCSs

Brand	Deployed ATCSs reported	Deployed ATCSs in database	Evaluation studies conducted*	Evaluations studies in database*
ACDSS	1	1	0	0
ACS Lite	6	6	8	7
Centracs Adaptive	8	8	5	4
P2P	9	1	1	1
D4	4	1	0	0
InSync	44	34	36	31
Intelight	4	1	0	0
Kadence	1	1	2	1
LADOT ATCS	2	2	2	1
OPAC	3	3	3	3
QuicTrac	1	1	1	1
RHODES	1	1	2	2
SCATS	10	10	19	18
SCOOT	4	3	6	6
SURTRAC	2	2	4	4
SynchroGreen	5	5	6	5
Transparity	17	1	1	1
Not specified	18	0	0	0
Total	140	81	96	85

*- Including evaluation studies of not deployed systems

Deployment and evaluation conditions

A particular ATCS deployment, as well as an evaluation study, are characterized by numerous factors. These factors were identified in the data framework for this project and integrated into development of the (AT)2C. Within each (AT)2C page several components of deployment and evaluation conditions are analyzed.

In the following sections various findings (made by using numerous filtering options) are discussed. These findings and relevant data summaries are presented in the order they are presented within the (AT)2C dashboards.

Basic agency information

This section covers findings related to the organizational context of agencies which deployed ATCS technologies. In addition, installation process and involvement of other agencies in the ATCS deployment is covered too. Organizational context of an agency is examined through various categories, such as, number of employees, training received to operate an ATCS, budget for ATCS operations and signal maintenance, and budget for capital traffic related projects categories. Qualified agency workforce represents one of the key factors for efficient ATCS deployment, maintenance, and operations. Size and expertise of the staff are some of the most important factors for a successful deployment of an ATCS. This general notion is reported by number of agency representatives on various ATCSs-related events (e.g., meetings, workshops). It needs to be noted that it is hard to simply quantify one's expertise since multiple factors (e.g., previous expertise, amount of training, in-house practice) can impact overall knowledge that

can potentially lead to a successful management of ATCS. This study provided just an attempt to quantifying agency experience through number of employees and duration of training received.

Figure 17 shows average number of employees and average number of training hours for all agencies (left) and all but few large agencies (which represent outliers) (right). The average number of employees includes all staff categories (i.e. manager, engineer, controller technician, and other technician).
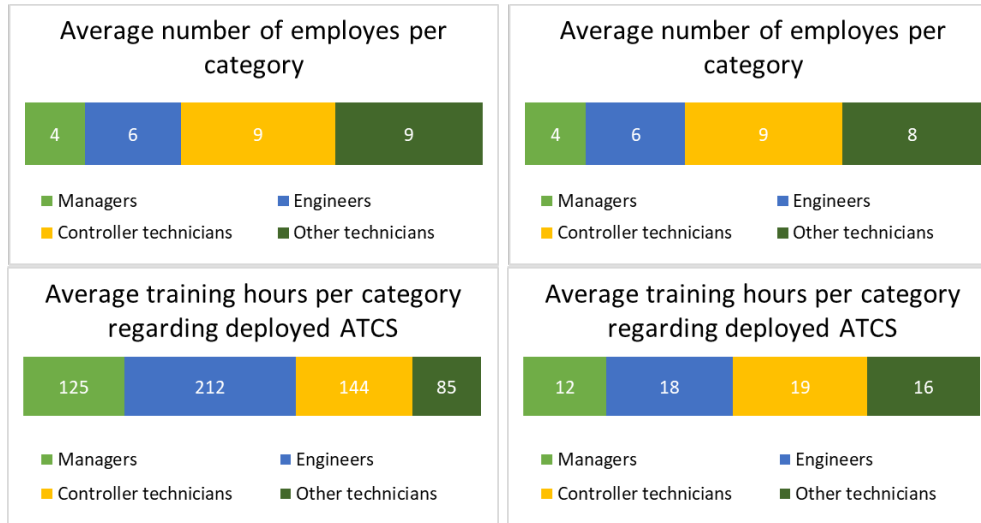
Figure 17 Agency workforce - all data (left), large agencies excluded (right)

It needs to be stated here that the average training hours are heavily weighted by a couple of agencies which have provided their employees with more than 3,185 hours of ATCS training. Considering that such heavy training practices are quite rare the number on the right (Figure 17) are much better representatives of common ATCS training practices.

Moreover, agencies' representatives were asked to assess need for additional stuff to help with day-to-day ATCSs operations. It was found that 10 out of 28 agencies need additional staff for this purpose. Cities seems to lack variety of employee categories (i.e., managers, engineers, technicians), county agency listed need for engineers and technicians only, whereas state agencies emphasized need for controller technicians at the first place followed by need for engineers without reporting lack of other employee categories workforce. However, there was no strong indication that additional training is needed. This is probably more a consequence of the fact that the agency representatives are unaware of complexities of the ATCSs than the fact that enough training was really received. Table 4 shows distribution, by entity type, of the agencies that reported need for additional staff to operate the ATCS.

Table 4 Number of agencies, by type, which need extra workforce to operate ATCS

Agency type	Number of agencies	% of total agencies
City agency	5	18
County agency	1	4
State agency	4	14
Total	10	36

Table 5 summarizes some of the operational categories for various agencies. This table is presented to give readers a chance to understand some of the basic traffic operational conditions of the agencies which participated in this study. It needs to be highlighted here that the total number of agencies given in Table 5 is higher than the number of agencies that participated in the survey. Those additional agencies were identified in the evaluation studies, but their analyses were not able to identify complete information (e.g.

their jurisdictional boundaries, number of ATCSs under operation etc.). Thus, it was assumed that such agencies operate at least one ATCS based upon evaluation study of the deployed system.

Table 5 Operational conditions for various ATCS-running agencies

	Agency	Cumulative length of the road network	Number of signals under operation	Number of coordinated signals under operation	Number of ATCSs under operation
1	Arlington county	*	*	*	**1**
2	California Department of Transportation - Los Angeles	>2,400 miles	>500	>300	1
3	City of Atlanta	*	*	*	**1**
4	City of Austin	>2,400 miles	>500	>300	4
5	City of Bellevue	<200 miles	200-300	130-200	1
6	City of Boca Raton	*	*	*	**1**
7	City of Chula Vista	*	*	*	**1**
8	City of Gahanna	*	*	*	**1**
9	City of Gresham	200-800 miles	100-200	<50	1
10	City of Harrisburg	200-800 miles	< 100	50-80	1
11	City of Huston	*	*	*	**1**
12	City of Madison	>2,400 miles	300-400	130-200	1
13	City of Menlo Park	<200 miles	< 100	<50	1
14	City of Norman	200-800 miles	100-200	80-130	1
15	City of Overland Park	200-800 miles	200-300	130-200	1
16	City of Philadelphia	>2,400 miles	>500	>300	>8
17	City of Pittsburgh	*	>500	*	**1**
18	City of Port St. Lucie	800-1,200 miles	100-200	<50	1
19	City of Portland	*	*	*	**1**
20	City of Renton	*	100-200	*	2
21	City of Santa Clarita	800-1,200 miles	100-200	130-200	>8
22	City of Stautnon	<200 miles	< 100	<50	1
23	City of Waterloo	800-1,200 miles	200-300	80-130	4
24	Cobb County	*	*	*	**1**
25	Collier County	800-1,200 miles	200-300	130-200	1
26	Colorado Department of Transportation - Greeley	800-1,200 miles	100-200	50-80	1
27	Colorado Department of Transportation - Woodland Park	*	*	*	**1**
28	Florida Department of Transportation - Miami	200-800 miles	< 100	<50	1
29	Florida Department of Transportation - Tampa	800-1,200 miles	>500	>300	7
30	Illinois Department of Transportation - Springfield	*	*	*	**1**
31	Lake County Division of Transportation	800-1,200 miles	100-200	80-130	2
32	Maryland DOT State Highway Administration - Hanover	>2,400 miles	>500	>300	8
33	Minnesota Department of Transportation - Minneapolis	*	*	*	**1**
34	Missouri Department of Transportation - Jefferson City	>2,400 miles	>500	>300	10

	Agency	Cumulative length of the road network	Number of signals under operation	Number of coordinated signals under operation	Number of ATCSs under operation
35	Missouri Department of Transportation - Kansas	*	*	*	**1**
36	Nevada Department of Transportation - Las Vegas	*	*	*	**1**
37	New Jersey Department of Transportation - New Brunswick	*	*	*	**1**
38	New York State Department of Transportation - Albany	*	*	*	**1**
39	New York State Department of Transportation - White Plains	*	*	*	**1**
40	Orange County Public Works	*	*	*	**1**
41	Oregon Department of Transportation - Salem	*	*	*	**1**
42	Palm Beach County	*	>500	>300	4
43	Pennsylvania Department of Transportation - Allegheny	*	*	*	**1**
44	Pennsylvania Department of Transportation - Bridgeville	*	>500	200-300	>8
45	Pinellas County	*	*	*	**1**
46	Road Commission for Oakland County	>2,400 miles	>500	>300	1
47	Seminole County	*	300-400	*	**1**
48	Utah Department of Transportation - Salt Lake City	>2,400 miles	>500	>300	>8
49	Virginia Department of Transportation - Fairfax	*	*	*	**1**
50	Virginia Department of Transportation - Richmond	>2,400 miles	>500	>300	>8
51	Volusia County	*	*	*	**1**
52	Wakefield Public Works Department	<200 miles	< 100	<50	1
53	West Goshen Township	<200 miles	< 100	<50	2
54	West Virginia Department of Transportation - Division of Highways	*	>500	80-130	**1**

*- No data reported; **bold values** – based on reviewed studies

Figure 18 show length of the network and number of signals under agency's jurisdiction. It can be observed that around 35% of the agencies have more than 2,400 miles under their jurisdiction. On the other hand, around 65% of agencies operates with less than 1,200 miles (where number of signals is not evenly distributed). Similarly, Figure 19 shows number of coordinated signals within deploying ATCSs agencies.
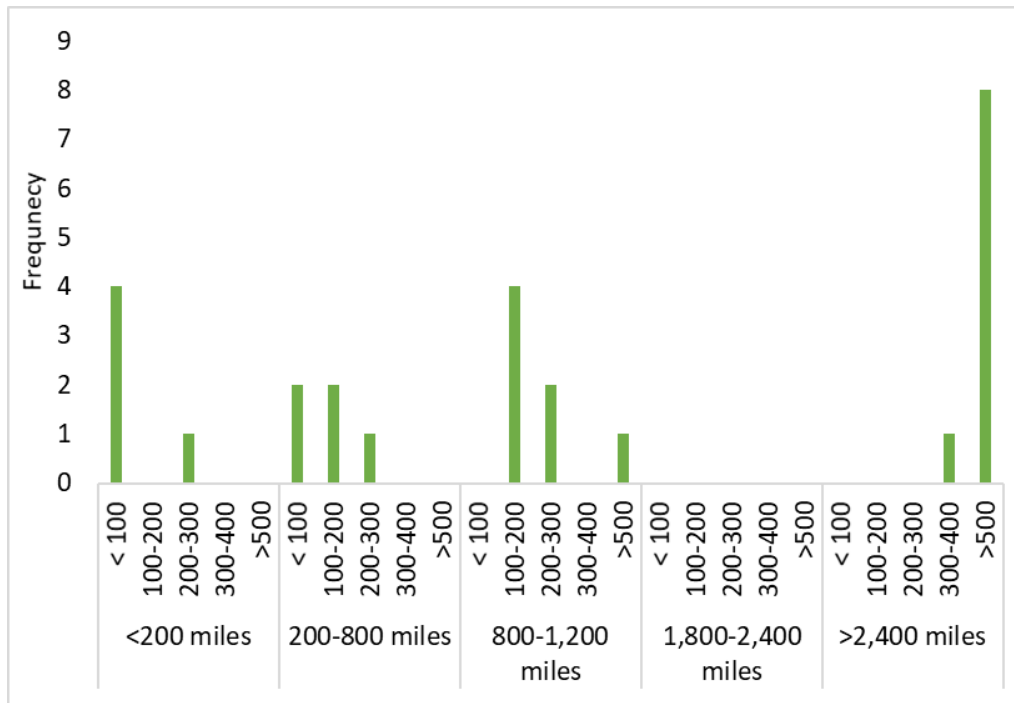
Figure 18 Road network coverage versus number of signals under operation

Based on the gathered data, Figure 19 shows that around 35% of the surveyed agencies operate more than 300 coordinated signals. On the other hand, around 31% of agencies operate less than 80 coordinated signals. Other stratified groups can be observed as well from Figure 19.

■ <50 ■ 50-80 ■ 80-130 ■ 130-200 ■ 200-300 ■ >300
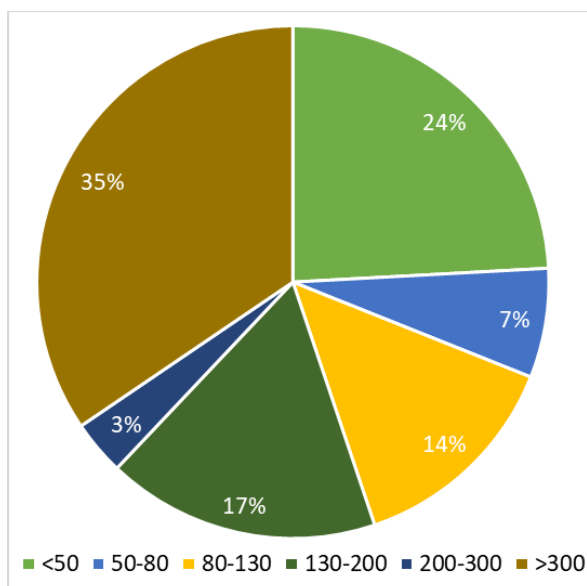
Figure 19 Number of coordinated signals within agency

While some of the ATCSs require significant infrastructural improvements (e.g. improving and upgrading detection layout, type, etc.) the other systems can operate well with the existing infrastructure, thus reducing overall time needed for installation. Based on the 34 reported deployments, it can be

concluded that around 50% of all ATCS deployments happen within a period of three months. Another 33% of the systems take anywhere between 3 months and a year to get fully deployed. Finally, there are some outlier installations which took more than a year to be finished (around 18%). Distribution of the ATCS s installation times are presented in Table 6.

Table 6 Duration of ATCS installation processes

Duration	Number of systems	Percent of total deployments
Less than three months	17	50
Between 3 and 6 months	8	24
Between 6 and 12 months	3	9
Between 1 and 2 years	4	12
More than 2 years	2	6

As stated above, duration of system installation is an important aspect of an ATCS deployment. This installation time can be factor of the ATCS brand as various ATCS brands may have different infrastructural requirements, which in turn may impact time necessary to install a system. Figure 20 shows an average duration of ATCSs installation per an ATCS brand. In addition to these two variables (average installation time and ATCS brand), Figure 20 also shows how many deployments are recorded for each ATCS brand to give a reader perspective of the bases for calculation of the average installation times.
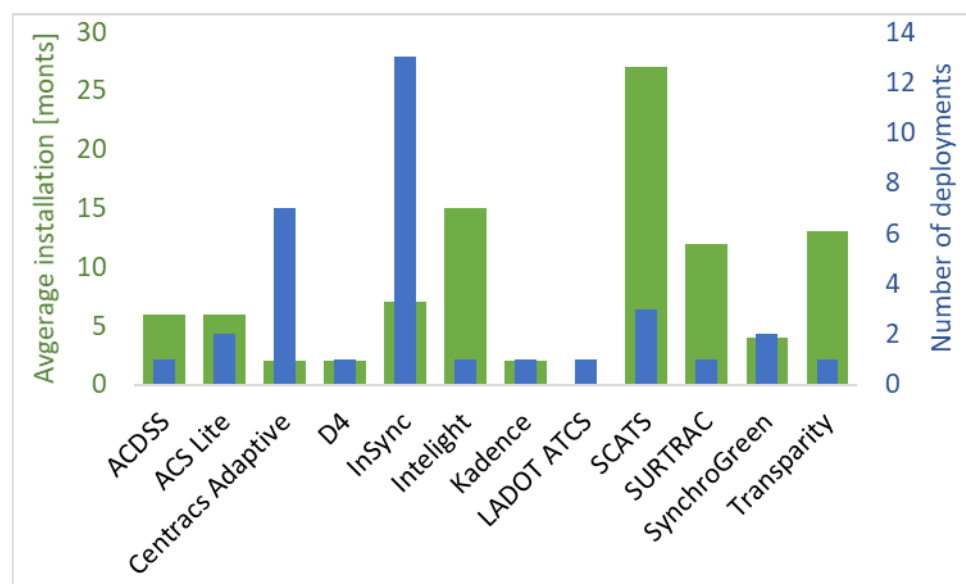
Figure 20 Average installation timeframe for various ATCS brands

Delays in ATCS installation can occur for a number of reasons but it is important to understand what the major reasons which cause such delays are. For all reported deployments (in total 51) it was found that installation delay occurred with only 7 deployments. The main contributing factor for installation delay were technical problems, whereas the second most influencing factor was poor coordination between installation vendor and deploying agency. It needs to be highlighted that detection, communications or problems with equipment were grouped under technical problems in the survey for deploying ATCSs agencies in order to keep size of survey manageable. These, and other, factors for installation delays are illustrated in Figure 21.
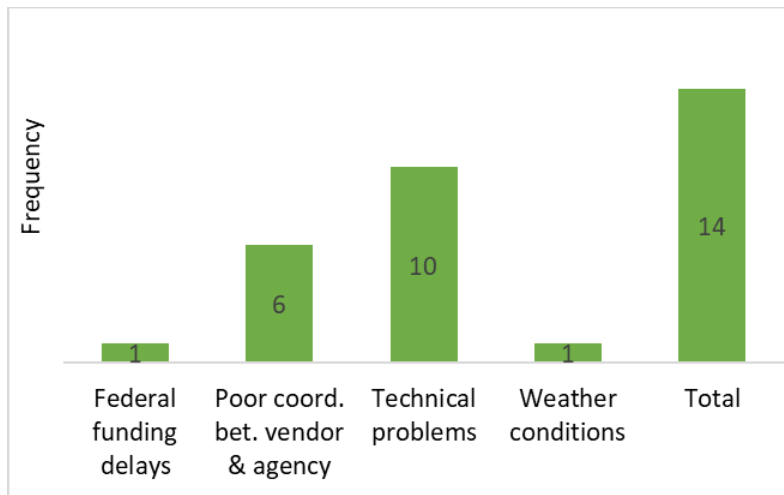
Figure 21 Reasons for delay of ATCS installations

For reported 51 out of 84 deployed ATCSs, 40 are currently fully operational thus representing 78%-share of all of the reported deployments. For the rest of the population a system is partially operational in 10% of the cases, and such systems are used with a limited scope or in combination with TOD plans. However, for 10% of the deployments (i.e. five), a system is partially decommissioned (the ATCS technology is present, not in use, but such a system can be easily switched ON in future). In two cases an ATCS is fully decommissioned, as shown in Table 7.

Table 7 Current status of deployed ATCSs

Status of deployed ATCSs	Percent of deployments
Fully operational	78
Partially operational (i.e., system is used with a limited scope or together with TOD plans)	10
Partially decommissioned (technology still there but not used; can be easily switched ON in future)	10
Fully decommissioned	2

Reasons (and frequencies) for ATCS decommissions (partial or full) are shown in Figure 22. The main reasons for decommissioning the ATCS are: detection and communication problems, incompatibility of deployed ATCS with agency's expectations, and maintenance issues (listed as other in Figure 22).
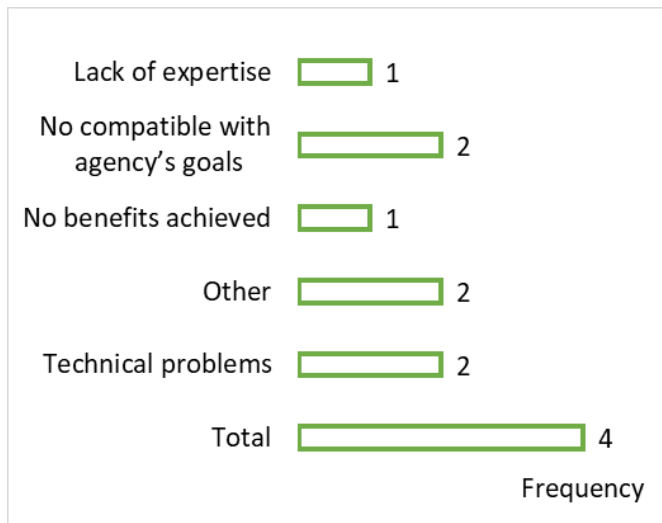
Figure 22 Reasons for decommissioning ATCSs

Out of 75 reported ATCS, in 26 cases an ATCS was deployed in order to improve conditions of urban traffic flows, as shown in Figure 23. It is found that handling traffic variability was second most important reason for deployment of adaptive technology (17 cases). In 13 cases agencies deployed an ATCS as this technology was seen as a profitable (high B/C ratio) solution considering installation costs and potential operational benefits. An equally important (12 cases) reason for ATCS implementation was to handle over-saturated conditions and day-to-day traffic variability. Some less common reasons for ATCS deployments were to handle traffic during special events, availability of funding for capital investments, and to act as an early deplorer of innovative technology.
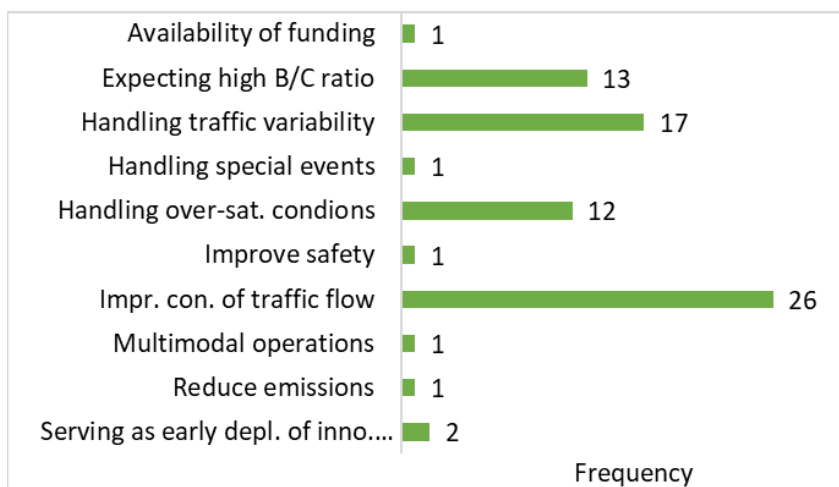
Figure 23 Main reasons for ATCS implementations

Involvement of different stakeholders and other agencies in the process of ATCS installation (and decision making process), is important for several reasons: (i) to ensure that needs and priorities of other stakeholders are recognized within deploying agency (for example, need for public transit priority), (ii) to allow for the fact that system goals are sometimes defined by other authorities (i.e., metropolitan planning organizations), (iii) to avoid jurisdictional overlapping (in the case where particular network is under mixed jurisdiction, all stakeholders need to be involved), etc.

Out of 56 deployments, in 35 cases, other DOTs, Counties or Cities were involved in the process of ATCS deployment, as shown in Figure 24. In 14 cases there was no involvement from anybody except the agency who carried the entire deployment process. Few of the systems were deployed as a result of mutual collaboration of the main deploying agency and a metropolitan planning agency, university, or another party.
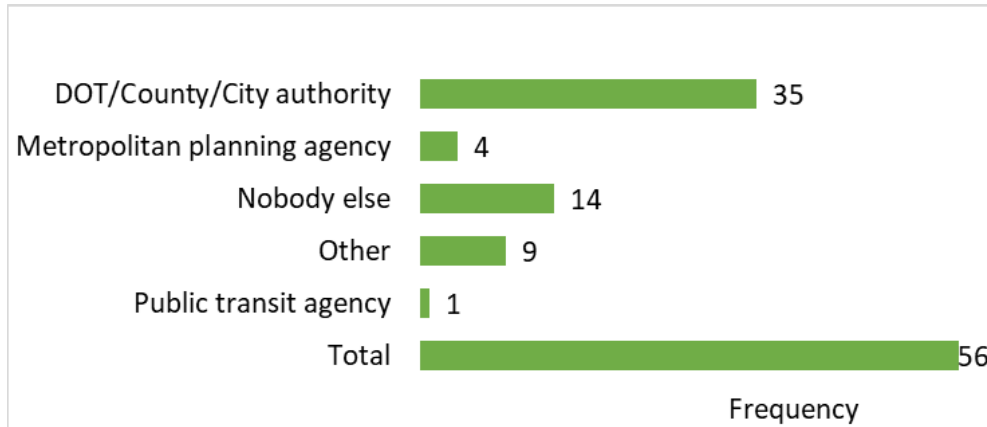
Figure 24 Involvement of other agencies in ATCS installation

Operational conditions

This section examines operational conditions of deployed ATCSs. Each deployment is characterized by a number of factors such as: prevailing traffic conditions (i.e. AADT on busiest road where ATCSs is deployed), system characteristics (e.g., proximity to multimodal operations, network size), integration of existing infrastructure with new and emerging technology (e.g., vehicle-to-infrastructure, vehicle-to-vehicle technology, etc.), alignment of agency objectives and system operations objectives (e.g., delay reduction) and system monitoring.

An area type of a deployed ATCS is usually a combination of various road network types, area densities, and network shape characteristics. Moreover, each area type has distinctive traffic demands, conditions, and patterns. Four different area types are defined (for the purpose of this study): central business district (CBD), urban area, suburban area, and rural area. It is less likely that ATCS deployment will occur in some rural areas, however this type was included to cover all possibilities. The findings from the gathered data show that 54% of the ATCSs were deployed within urban areas, 27% within suburban areas, 17% of the deployments area type was not specified, and for 1% in CBD. No deployments within rural areas were recorded.

Network type is another important factor to understand where the ATCSs may be more (or less) successful. Some ATCSs work better on linear corridors while the others are more beneficial on grid or irregular networks. The findings from the recorded data show that 63% of ATCSs were deployed on a single corridor. In 19% of the deployments, an ATCS was installed on two intersecting corridors or mixed (i.e., irregular, nor single corridor, nor grid) network type. For remaining ATCS deployments, a network type was not specified. Both data for area type and network type are shown in Table 8.

Table 8 Number of ATCSs for various area and network types

Area type	Number of deployments	Network type	Number of deployments
Urban area	44	Single corridor	51
Suburban area	22	Two intersecting corridors	7
CBD	1	Mixed	8
Not specified	14	Not specified	15

Frequencies of the ATCS deployments for various area and network types can be also observed in Figure 25. It is found that, for almost every area type (excluding CBD), the most dominant network type is single corridor. In a typical urban setting ATCSs were deployed on other network shapes (e.g., two intersecting corridors, mixed) in a greater number compared to the suburban areas. This finding aligns with a common belief that ATCSs are installed more on networks (as opposed to corridors) in highly urbanized environments. However, it needs to be highlighted that a very small number of deployments were reported (and found in the literature) for CBDs and grid networks.
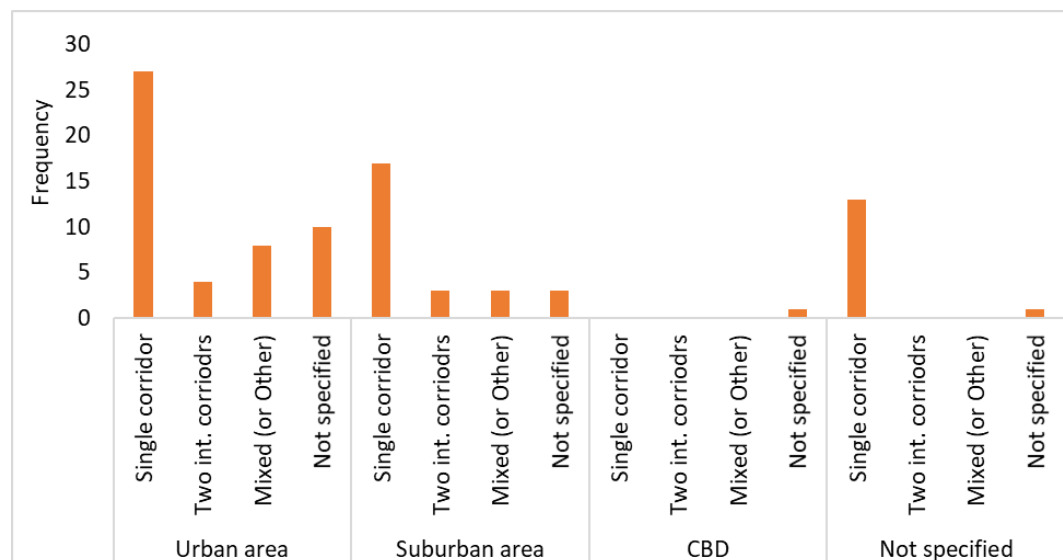
Figure 25 Distribution of deployed ATCSs per urbanized area and network type

Temporal and spatial traffic fluctuations are inevitable in the transportation networks. It is difficult to provide a single measure which can properly describe prevailing traffic conditions on a road network. However, one way to characterize traffic fluctuations is a maximum volume recorded on the network, of deployed ATCS, which an ATCS needs to accommodate. Thus, an AADT on the busiest road on deploying ATCS network category is used as an intuitive, and easy to obtain, measure for signal technicians and other users. This measure can provide a good insight on the level of traffic demand that an ATCS needs to process. Figure 26, for example, shows a distribution of AADTs on the busiest roads where the recorded ATCSs are deployed. Based on 61 deployments, the findings show that around 30% of the deployed ATCSs basically accommodate range of AADTs between 35,000-45,000 vehicles per day. Similarly, around 20% of the ATCSs work with AADTs between 25,000 and 35,000, whereas around 20% of ATCSs accommodate AADTs of less than 25,000 vehicles per day. Finally, around 26% of the ATCS deployments are on the networks where the busiest road carries more than 45,000 of vehicles per day (AADT). This is an attempt to generalize relationship between ATCS distribution and heaviness of traffic but more detailed AADT data can be easily retrieved, for each deployed ATCS, form the (AT)2C's database.
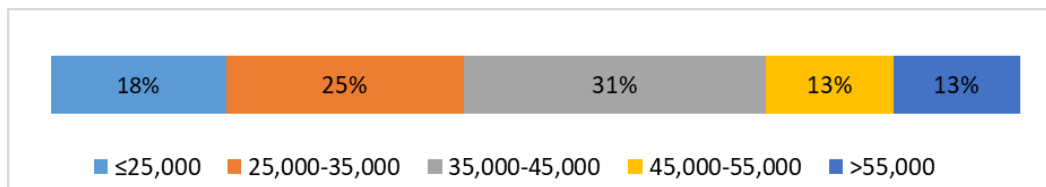
Figure 26 Distribution of ATCS deployments based on relevant AADT volumes

Another interesting information about ATCSs is a number of traffic signals which are under ATCS operations. Obviously, this number will depend on the total number of signals operated by an agency but for those agencies which have a considerably higher number of total signals than those operated under an ATCS – it may show how seriously interested the agency is in ATCSs in general (or in a particular ATCS brand). Figure 27 shows, for example, that around 65% of surveyed agencies operate between 5 and 15 signals under an adaptive control regime. This information raises a flag as it shows that around two thirds of all of the reported ATCS deployments actually represent either agencies with small number of signals or those which are still in a phase of testing an ATCS. Only ~15% of the agencies have ATCS deployed on a network containing 30 or more traffic signals. This essentially means, that we still have not 'sold' the benefits of ATCS technologies to large agencies or they have not had enough resources for a massive deployment of ATCSs. However, these statements are more speculations than statements based on the hard facts. Additional cross-referencing between data in the database and potentially other external data is needed before we can add significant reliability to such conclusions. However, it is important to note here that every user of the (AT)2C has ability to cross-reference the data in so many different ways (and come up with more or less valid speculations and conclusions).
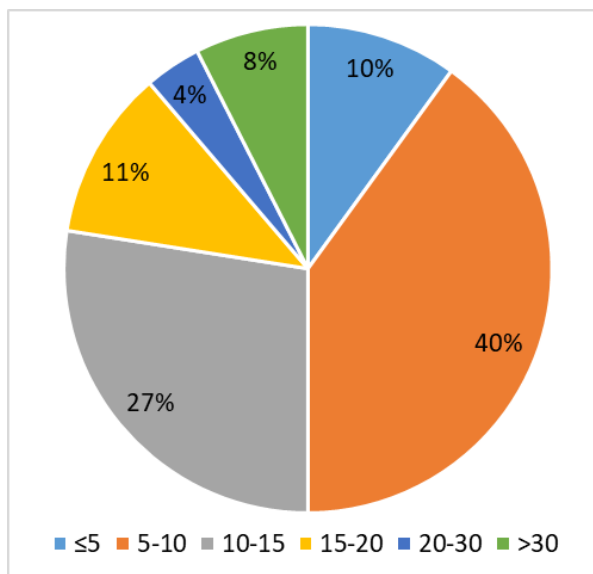
Figure 27 Distribution of ATCSs with various numbers of signals

Another way of looking at ATCS coverage is not by number of traffic signals but by a length of the road network which is covered by those signals. Although a bit unorthodox this measure works well for less urban environments where larger distances are covered with few sparse ATCS signals. Table 9 shows a distribution of ATCS deployments based on the length of network (in miles) covered by such deployments. It is observable (from Table 9) that around of 53% of deployed ATC systems, cover a network length of 3

miles or less. One of the potential reasons for this finding is that most of the deployed systems are found on single (linear) corridor.

Table 9 Frequency of road network coverage under ATCSs

Length of network under ATCSs [miles]	Number of deployments	Percent of deployments
<3	42	53
3-6	24	30
6-9	4	5
9-12	3	4
>15	7	19

Another interesting insight about ATCS operations is to look into relationship between these systems and multimodal operations i.e., does a deployed ATCS enable/support multimodal operations? This type of question may not be a detailed enough to uncover specifics of multimodal integration in the ATCS. However, given the limitation of obtaining this type of information through a survey, this feedback is supposed to give a user at least a glimpse of how well multimodal operations (such as railroad preemption, transit signal priority, pedestrian and bicycle operations) are integrated in ATCS. The assessment was done on an increment scale of 5, where 5 meant fully utilized and 1 (the lowest score) meant – not utilized at all. Figure 28 shows to which extent each of the multimodal aspects was utilized by the ATCSs whose operating agencies participated in the survey.
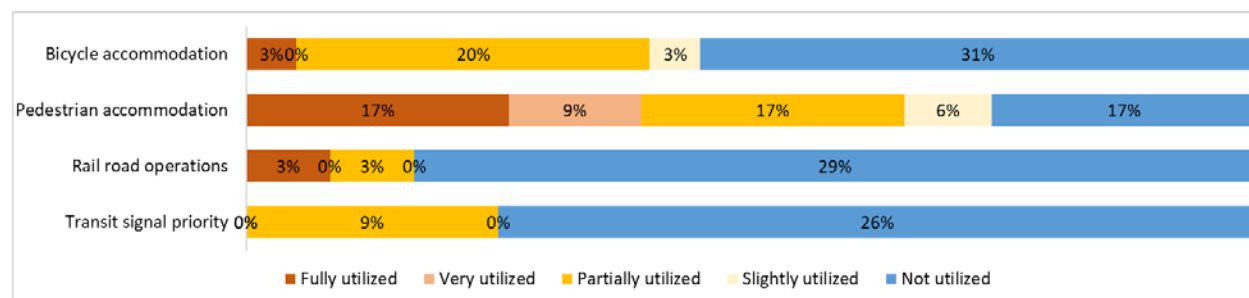
Figure 28 Percentage of ATCSs utilizing various multimodal operations

It should be noted here that the cases where multimodal operations were not included in ATCS (a user chooses 'NA' as an answer) were excluded from the results shown in Figure 28. The findings from Figure 28 show that the most utilized aspect of multimodal operations are pedestrian operations. In a similar fashion railroad and bicycle operations are utilized in around 3% of all of the examined deployments. There is a whole range of findings related to partial utilization of the multimodal features, varying from 3% for railroad operations to maximum of 20% for bicycle operations. It is interesting to note that multimodal operations are not utilized in 17% of the deployments for pedestrians and to 31% for bicycle operations.

In a similar fashion, Figure 29 summarizes experiences of ATCS-deploying agencies of integration of existing ATCS infrastructure deployed with new and emerging technologies (i.e., vehicle-to-infrastructure and vehicle-to-vehicle communications) and capability to use high-resolution data.
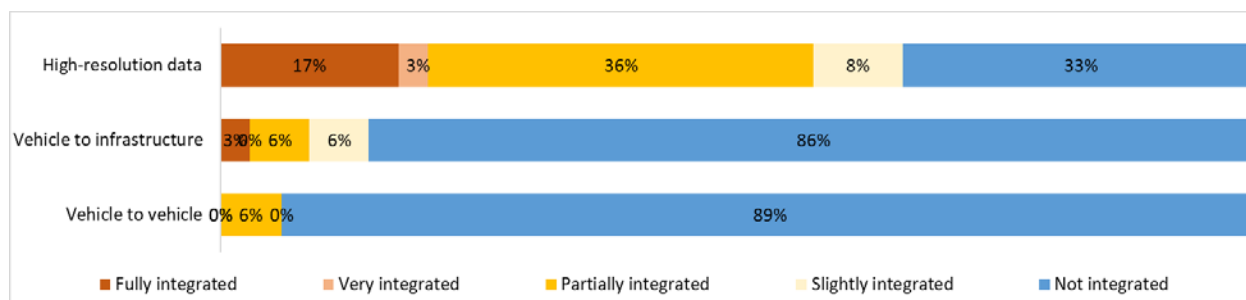
Figure 29 Percentage of ATCSs utilizing emerging technologies

In order to better understand a context of ATCS integration with new and emerging technologies it is necessary to provide temporal component of deployed ATCSs. The temporal component is important since various new technologies emerge at various times and some of the older ATCS deployments may not be highly relevant for consideration. Table 10 helps to understand this chronological context of ATCS deployments by showing a distribution of time periods when ATCS deployments have been initialized. Data from Table 10 show that a significant percentage (58%) of ATCS deployments have been initialized within the last five years. In addition to that around 11% of the ATCS deployments started in the period between 2010 and 2014, whereas 11% of the ATCSs are older than 2009. Finally, for 19% of the ATCS deployments there were no responses on the time of their installation.

Table 10 Chronological distribution of initialization of ATCSs deployments[*]

Time period	% of deployments
2015-2019	58
2010-2014	11
≤ 2009	11
Not defined	*19*

*year when an ATCS becomes fully operational is used for this analysis

Based on the 36 reported ATCS deployments with integrated emerging technologies, where 58% of those systems are deployed between 2015 and 2019, it is shown that 64% of ATCSs have been enabled to support high-resolution data recording. This trend can be partially attributed to the fact that all of the new controllers (which are often upgraded when an ATCS is installed) are capable of supporting high-resolution data recording. On the other hand, only 15% of the deployed ATCSs have some integration with vehicle-to-infrastructure communication technologies. Further, it was found that 60% of the ATCSs that support some vehicle-to-infrastructure (V2I) technologies were deployed within the last five years (e.g., 2015-2019). For remaining 40% of deployed ATCSs with some V2I integration, deployment years were not reported. More details about particular V2I technologies were not provided in the answers to the survey. Interestingly, the vehicle-to-vehicle communication technologies are integrated in 6% of ATCS deployments.

Operating multiple ATCSs (potentially of different brands) by a single agency can require additional workforce and training, if the deployed ATCSs are to be fully utilized. Out of 29 surveyed agencies, 14 agencies (or 48%) operate more than one ATCS, which is a bit of surprising finding. If one further investigates variety of brands among the deployed ATCSs, the data show that five agencies operate multiple (>1) ATCSs of different brands (e.g., operating two systems, SCATS and InSync), whereas nine agencies operate multiple ATCSs but of the same brand (e.g., operating two systems SCOOT systems). It was further found that in most cases, (6 out of 9) agencies that operate multiple ATCSs of the same brand have deployed up to four such systems. Interestingly, the data shows that when a number of ATCS deployments increase to more than 4 (per agency) it means that an agency deploys multiple ATCS brands. Finally, a closer examination of the ATCS installation timelines show that cases when agency have deployed multiple ATCSs of the same brand almost exclusively occurred in the last four years. This finding can raise a

question if those multiple ATCS installations have been given enough time for proper field evaluation and to get a chance to properly mature in the agency's institutional setting.

In the next step we examined how agencies monitor their deployed ATCSs, especially in the environments of multiple ATCSs of different brands within the same agency. The findings show, as illustrated in Figure 30, which in 64% of cases an ATCS is individually operated, while in the rest of cases (36%) multiple systems are operated from one central platform. In addition, it was found that in all cases when an agency has multiple ATCSs of different brands, such systems are monitored individually (i.e., each system has its own platform). For those agencies that operate multiple systems from a central platform, it was found that a number of deployed ATCSs was up to four. These trends show (logically) that as the number of ATCS brands increase within an agency, the agency is inclined to decentralize its monitoring practices. However, it is not sure if this finding is correlated with real reasons for deploying different brands under the same agency (such feedback was not reported).
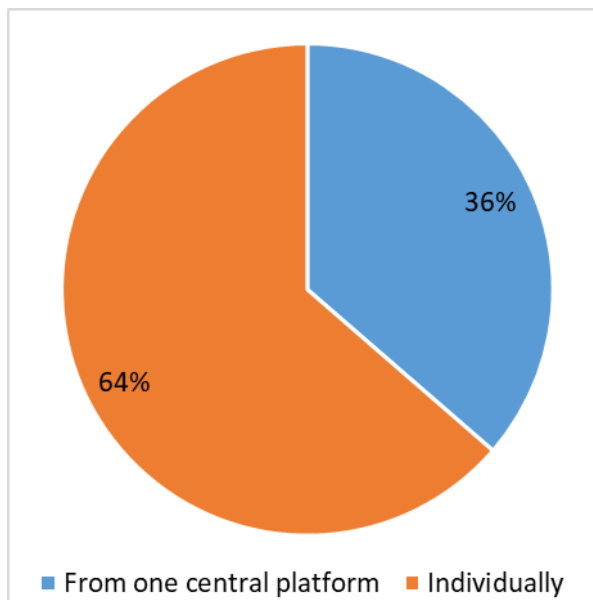
Figure 30 Proportion of ATCSs with various monitoring options

In the past times, ATCSs were often seen as systems which are difficult to understand and operate (often referring to protectiveness of their logic and algorithms as 'black boxes'). The survey questions allowed us to assess how the interviewed agencies perceive their ability to understand the working principles of their ATCSs. While the nature of such a question is a bit biased (most people will not admit publicly that they do not understand how their systems work), if the respondents are given a sensitive scale of answering options their answers may reveal a potential issue. The results of our survey show that around 71% of agencies find that working principles of their ATCSs are either understandable or very understandable (shown in Figure 31). The remaining portion (of around 30%), however, find that they do not have a very good understanding about how their ATCSs work. These findings show a potential increase in the level of familiarity with ATCS operations in general, when compared with some past studies (Stevanovic, 2010). This increase in familiarity with the ATCSs can be attributed to the fact that the rate of ATCS installations has increased significantly in the last few years thus leading to a higher level of ATCS knowledge dissemination in the traffic engineering community.
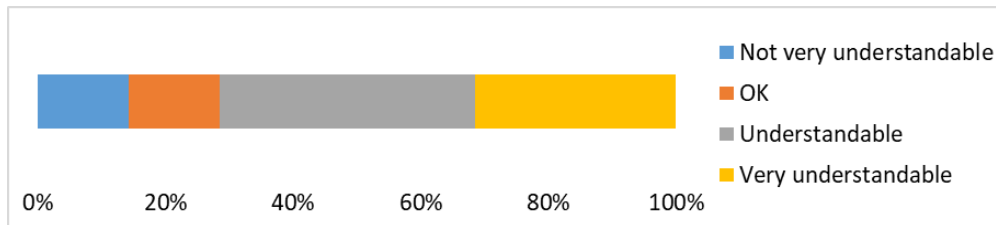
Figure 31 Percentage of agencies with various understanding of ATCSs' principles

Ability of an ATCS to adjust signal timing parameters in real time is one of the most important features (and signs of system capability) for adaptive operations. While operating in adaptive mode, some ATCS brands adjust all major parameters (such as cycle length, phase splits, offsets, and phase sequence) depending on prevailing traffic conditions while the others adjust only some of these parameters. Figure 32 shows how many of the deployed ATCS adjust various signal parameters, among the surveyed ATCSs. Out of 33 surveyed ATCSs 31 adjust both offsets and splits while the frequency of adjusting cycle lengths is somewhat lower. Understandably the phase sequence is the least adjusted signal timing parameter; this can be a consequence both of an ATCS-brand's inability to modify a phase sequence as much as agency's unwillingness to play with this setting in real-time fashion.
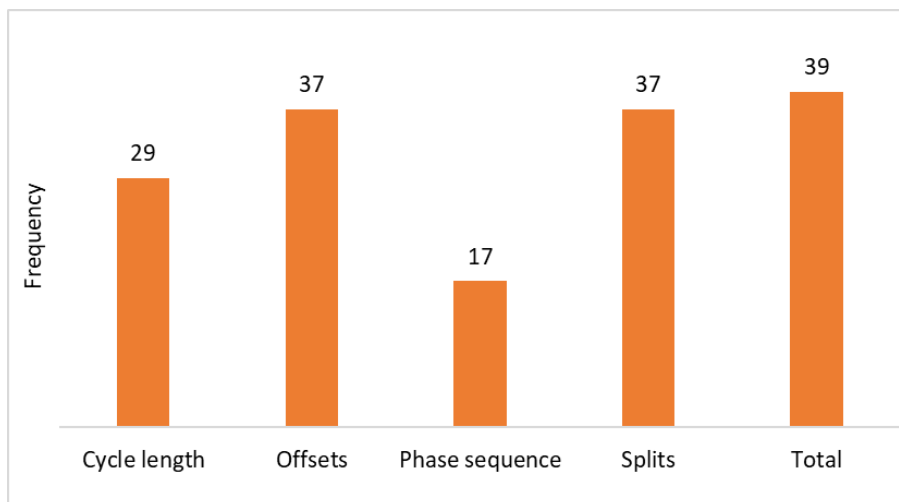
Figure 32 Frequencies of ATCSs with various signal timing options

Major operational objectives are another important concept to know about an ATCS deployment. Each ATCS brand can have its own operation objectives. For example, an agency may install an ATCS brand which (claims to) maintains good progression on the main corridor. However, if the main corridor has several high-volume pedestrian crossings, the deployed ATCS may have limited ability to integrate pedestrian operations into main-corridor progression unless the system has ability to do so. Thus, crucial importance that these two objectives are aligned in order to have an effective adaptive system.

Figure 33 shows a set of performance measures which were offered to the surveyed agencies to provide their assessment on the level of their improvements upon the deployment of the ATCS. Before we go into any discussion of the findings a reader should know that an answer option "NA', which was also offered to the respondents, was excluded from the Figure 33. This exclusion explains why none of the stacked bars reach the total value of 100%. On the first glance at Figure 33 it can be seen that for those performance measures which are mainly based on main-street traffic flows (such as delay, travel time, number of stops, queue lengths, emissions and fuel consumption), agency representatives find ATCS to be beneficial (agree or strongly agree) in most of the cases. These numbers vary from 41% for queue lengths to 78% for travel

times. However, for performance measures related to ATCS operations on the side street the ATCS benefits are much less convincing. Similarly, it does not seem that the agencies see significant benefits from ATCS for multimodal operations or to impact safety of the traffic operations. However, it should be noted that these are somewhat subjective opinions of the relevant agencies' staff and not necessarily assessments based on the quantitative data.
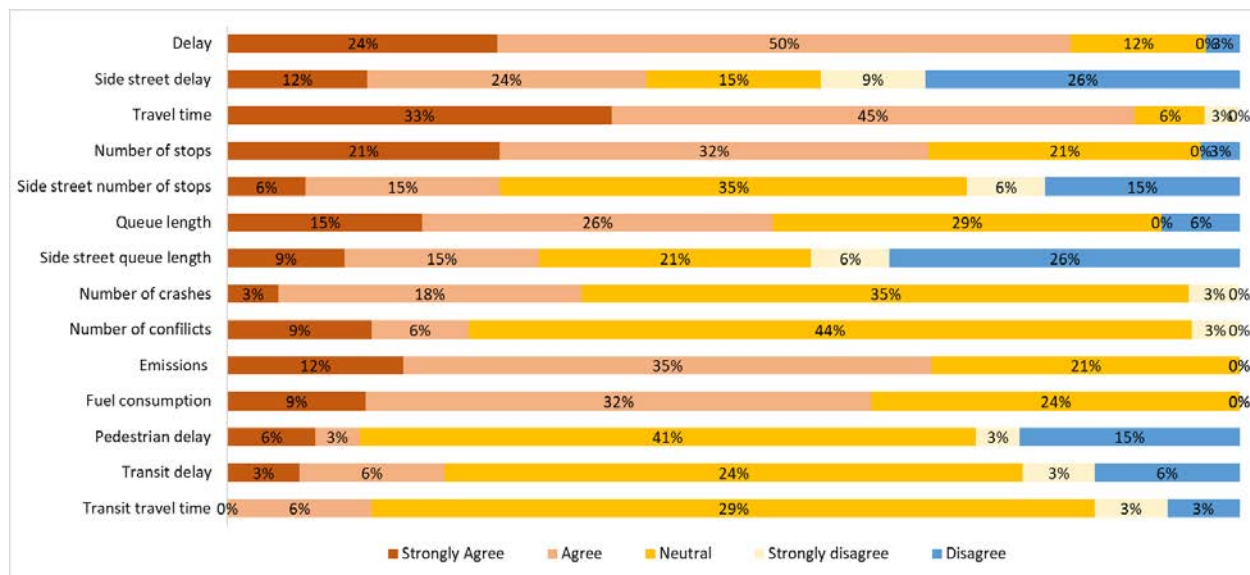
Figure 33 Perception of agencies on ATCS's improvement of performance measures

Infrastructure & costs

This section covers infrastructure and costs of the deployed ATCSs. Such costs include: capital costs for ATCS hardware, software (licensing), detection and communication equipment, and costs for system operations and maintenance. In addition, this section examines pre-ATCSs operational environment, such as pre-ATCS signal retiming/fine-tuning frequency, existence of coordinated operations on the network under ATCS, etc.

There are several different mechanisms that agencies follow to select and procure ATCSs. The two main approaches are procurements through competitive bidding or sole-source acquisitions. The competitive bidding represent a process where a deploying agency provides in-depth specifications for the adaptive project and invites vendors (contractors) to bid to get the job. Competitive bidding aims at obtaining goods and services at the lowest prices by stimulating competition. On the other hand, with the sole-source approach, a deploying agency procures a particular (unique) system where such a decision is justified by the case that such a system is the only one that can fulfill agency's requirements. In addition to the selection process, some agencies may deploy a system only for a trial run where the system can be decommissioned if it has not met a set of criteria established by the deploying agency.

Figure 34 shows that in most of the cases (64%) the agencies deploy an ATCS based on the sole-source approach (i.e., considering only single ATCS brand). The completive bidding is used only in 15% of the cases, with a note that this does not have to mean that always the lowest-bid ATCS was selected. Finally, other selection methods were reported in 24% of deployments. Within the 'other selection method', the agencies did not directly participate in the selection process (e.g. selection of the system was based on state procurement) or another experimental or cooperative processes were used.
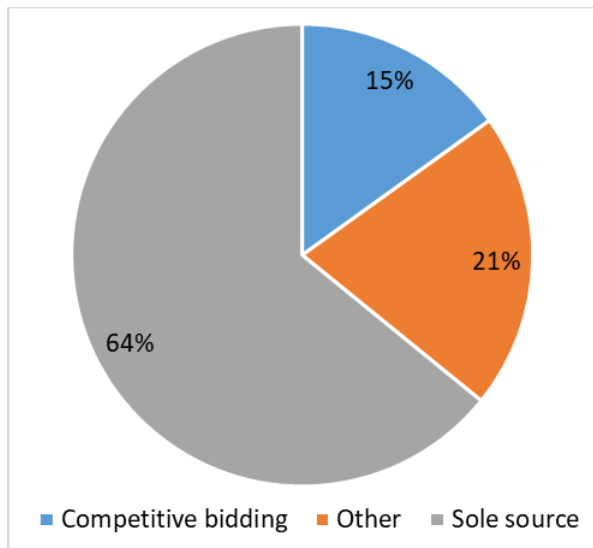
Figure 34 Distribution of methods used to select ATCS

Another important aspect for success of an ATCS is a type of traffic signal control that was used before an ATCS was deployed. Based on the type of traffic control (e.g. fixed-time versus actuated, or isolated versus coordinated) a significantly different amount of operational benefits could be achieved. Another important factor is frequency of regular signal retiming (or ad-hoc fine-tuning), which directly impact quality of pre-ATCS signal operations. For example, it is customary to expect that on networks operated by fixed-time or isolated traffic signals one can expect a higher level of operational benefits once an ATCS is deployed. On the other hand, well-maintained and regularly retimed traffic signals, with a decent detection and communications and a high degree of coordination, may not experience significant operational benefits from an ATCS (especially not until the traffic flow conditions change). For all of the ATCS deployments, we examined pre-ATCS signal operation type, coordination mode of operations, and retiming/fine-tuning frequency. Table 11 shows such a distribution of various pre-ATCS signal operation types. The findings show that in about two thirds of the reported cases the deployed ATCSs have replaced fully-actuated traffic signal systems.

Table 11 Percentage of pre-ATCS signal operation types

Signal operations type	% of deployments
TOD – Fixed	11
TOD – Semi-actuated	22
TOD – Fully actuated	67

In addition to that fact, Figure 35 reveals that very large majority of the pre-ATCSs enjoyed a decent degree of coordination with only few percent where the signals were fully isolated. This puts additional level of expectations on an ATCS as a potential room for improvements may be reduced by a good performance of pre-ATCS non-adaptive traffic control.
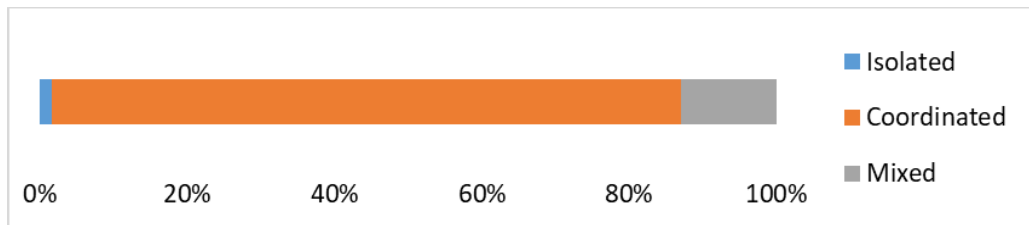
Figure 35 Distribution of pre-ATCSs signal operation modes

For non-adaptive traffic signal systems, it is necessary to retime traffic signals, either as a part of regular retiming programs or ad-hoc signal fine-tuning, usually resulting from public complaints. These two processes can have a significant impact on the quality of signal operations. For this reason, signal systems which had experienced regular and extensive signal adjustments before the ATCS deployment tend to show lower degree of benefits once the ATCS is installed; at least if the evaluation of the ATCS (e.g. before and after study) is performed soon after the ATCS deployment. Thus, a frequency of signal retiming or fine-tuning, may have significant impact on benefits of the ATCS. Figure 36 shows that for 69% of the ATCS deployments, signals were not retimed/fine-tuned at least once per year, which does not show a high level of signal maintenance/fine-tuning. On the other hand, more frequent (at least once per year) fine-tuning was reported for 31% of the ATCS deployments.
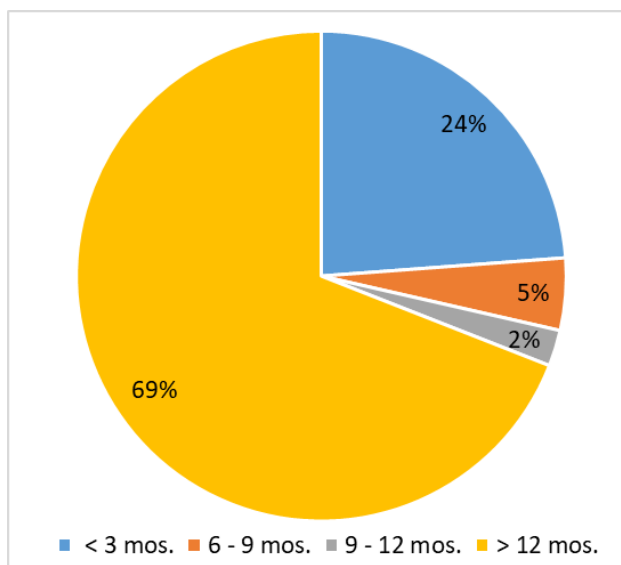
Figure 36 Frequency of pre-ATCS-deployment signal retiming

Detection layout and technology and communication infrastructure are of particular interest when it comes to ATCS deployment. First, a significant portion of the installation costs could be associated with upgrading of the pre-ATCS detection system. And secondly, those ATCSs which require a higher level of detection (either by coverage or sophisticated technology which may be vulnerable under some operational conditions) may require higher detection installation and maintenance costs. Also, improper detection can affect ATCS's operations and in some cases lead to decommissioning of the system.

Exact detection layout of an ATCS deployment depends on the deployed ATCS brand. Each ATCS brand will have a specific system of preferred detection layout and coverage (e.g. position, length of detection zone). However, most of the ATCS brands can also work with alternative detection layouts which usually lead to suboptimal performance. The most of the ATCSs work with stop-line (i.e. immediately upstream from the stop line) detection but many use various types of advance detectors which can be placed anywhere

from near-stop-line (i.e. few hundred feet upstream of the stop line) to the far-side exit point of the upstream intersection. Figure 37 shows that of the 36 reported ATCS deployments the most common are stop-line detectors (34 cases) whereas mid-block detectors are also frequent but the far-side detectors are the least frequently used. For other detection location types dilemma zone detectors were reported too but these arbitrarily belong to near-stop-line detection type.
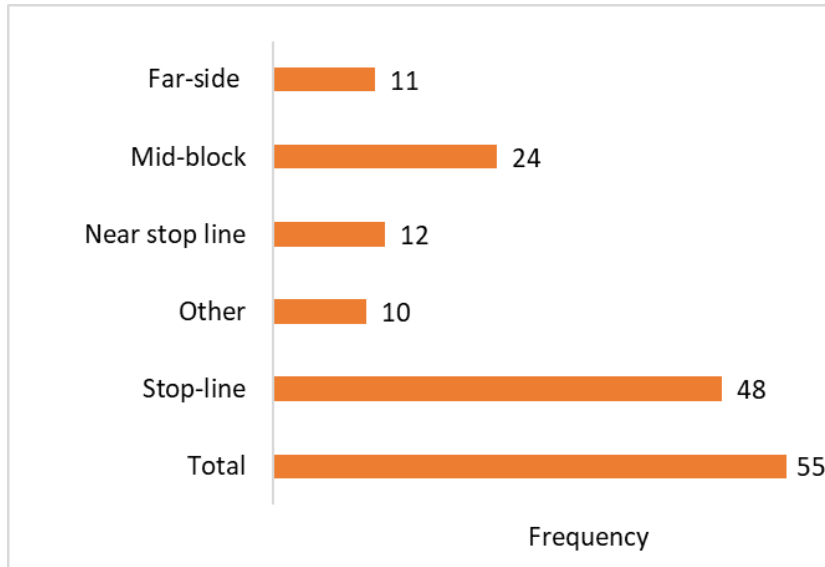
Figure 37 Frequency of various ATCS detection layouts

In the early days of ATCSs deployments, the inductive loops were primary type of detection technology. With emergence of noninvasive, and sometimes more cost-effective, detection technologies the ATCS's detection options has increased. Our data findings show that out of 55 ATCS deployments reported, 37 used two or more detection technologies. Figure 38 shows that video detection is the most frequently utilized detection technology is used, followed by inductive loops and microwave radar detection. A relatively new detection technology which advocates installation of in-pavement detector pucks has been used only in a couple of deployments, for two different ATCSs brands. Listed as other, thermal detection is used in one deployment in a combination with video detection, inductive loops, and microwave radars.
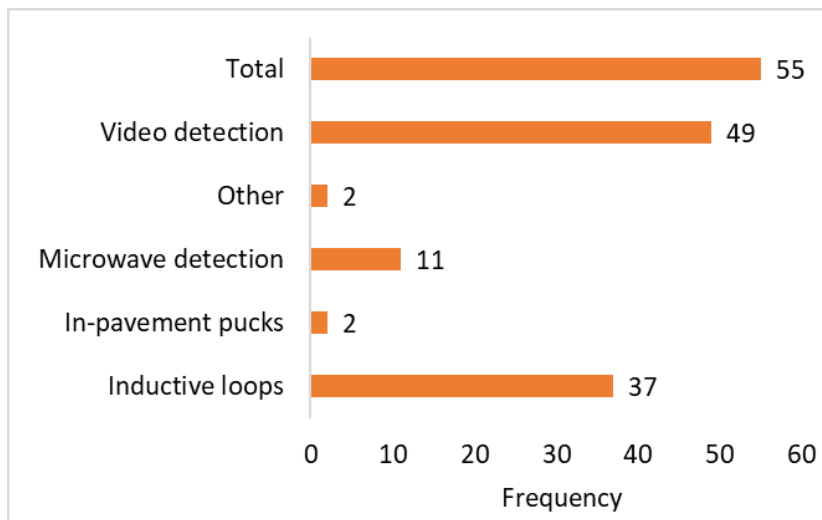
Figure 38 Frequency of various ATCS detection technologies

Communication between central ATCSs hardware/software and field traffic controllers usually requires a reliable transmission media. Figure 39 shows that out of 46 deployments surveyed, the most common type of transmission media is fiber optics, followed by twisted pair and wireless media. Other transmission media, such as telephone lines, microwaves, and cellular are rarely used.
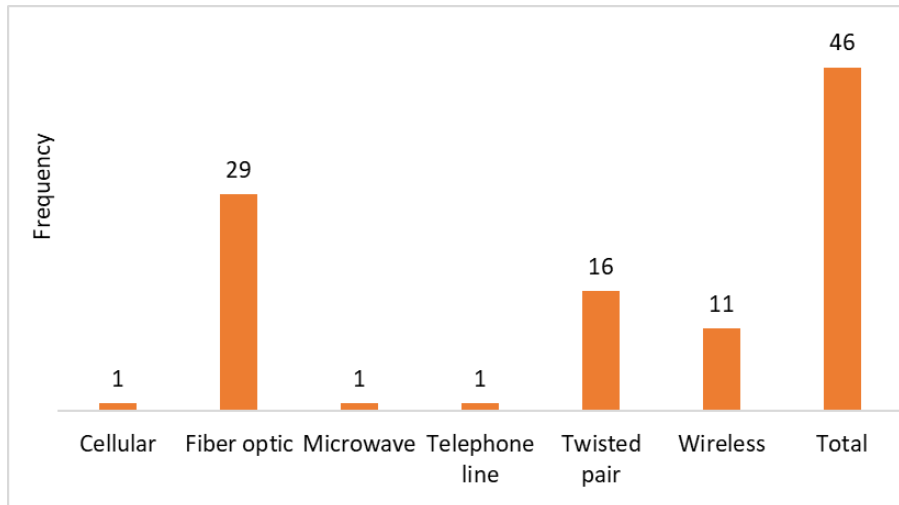
Figure 39 Frequency of communications media between ATCSs and field controllers

Costs of deploying and operating an ATCS depend on many factors. Thus, it is hard to isolate pure costs of installing adaptive component of the system. To illustrate this, installation of an ATCS on a network with good state of existing infrastructure (e.g. local intersections hardware and software, detection technology, layout, communication media, etc.) can be done at relatively low costs. On the other hand, if there is a need to extensively improve infrastructure (controllers, communications, detectors) to support the ATCS deployment, one should expect significantly higher installation. A special component of installation costs are ATCS licensing costs which can depend on: number of intersections under ATCSs, other relevant software (e.g. central management system), etc. In addition to capital installation costs, are the costs of maintaining the ATCS. Such costs may include consulting costs, costs of license renewal, and daily costs of operating ATCS hardware and software.

Based on the costs from 26 ATCS deployments, it was found that the total average costs per intersection are around $55,000 (as shown in Table 12). Previous studies (Stevanovic, 2010) report a similar yet slightly higher number (around $60,000). Surprisingly, this trend does not show a very significant change in the last ten years. We speculate that these findings can be attributed to two facts: 1. ATCS vendors may be more interested to make higher-margin profits than to increase market penetration by offering more affordable ATCS solutions, and 2. Most of deploying agencies still have to upgrade their infrastructure; so, the marginal contribution of pure ATCS costs is still relatively a small contribution in the overall signal system upgrade costs. However, the reviewed data show a relatively large range of variations of the installation costs. The minimum installation costs (per intersection) start from low $2,000 and they reach a maximum of $283,000. The data also show that the licensing costs of ATCS can go from zero (no license fees) to 56,000, which is quite a high ATCS licensing fee (per intersection) for current conditions. Finally, the maintenance costs can be as low as $300 per intersection per year but the highest annual maintenance cost has been recorded at $21,660 per intersection per year. As one can see from Table 12 we have a whole variety of different costs but an important thing is that current market allows such differentiation in the costs (e.g. installation, licensing, and maintenance). Few years ago, it was difficult to get those estimates altogether.

Table 12 Min, Max & Average costs of ATCS deployments

Value	Total costs of installation per intersection	Cost of ATCS license per intersection	Maintenance costs of per year per intersection
Minimum	2,000	0	300
Average	55,534	10,252	3,814
Maximum	283,000	56,000	21,660

When asked to compare their ATCS maintenance costs with the maintenance costs before the ATCSs were installed, the surveyed agency representatives reported that the costs of maintaining the ATCSs are almost the same for 19 out of 35 reported deployments. As shown in Figure 40, in 11 cases of the interviewed agencies responded that costs are higher whereas in 4 cases the agencies found that the costs of maintaining ATCSs are lower than the comparable costs before the ATCS was deployed. While these findings come with some surprise they show that the ATCSs may be more expensive than needed to be a competitive solution. On the other hand, higher ATCS costs may give more incentive to industry (vendors and consultants) to invest in these technologies even more as they clearly represent good business/profit opportunities. It is interesting to report that further investigation was performed to find out if there is a correlation between level of maintenance costs and particular ATCS brands. However, such (obvious) correlations are not found; in other words, it seems that a number of ATCS brands were equally associated with both low and high maintenance costs.
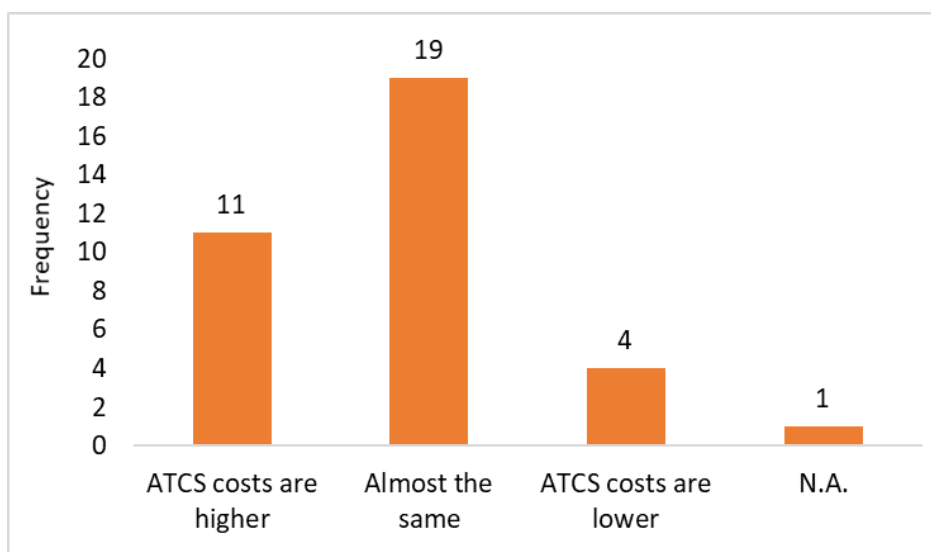
Figure 40 Perception of ATCSs and pre-ATCS-deployment maintenance costs

The next investigated aspect of ATCS operations was longevity of the deployed ATCS. From the first ATCS implementations to nowadays probably a several hundred of ATCSs were deployed. For various reasons (e.g. operational, institutional, financial, maintenance) many of the early deployments were decommissioned (either partially or fully). However, some of early deployed systems (although most likely not in their original configurations), have been operating until nowadays. Based on the current status of deployed ATCSs, and year when the systems became fully operational, it is possible to compute their lifespans. Table 13 summarizes such a distribution of lifespans (given in 5-year increments) of the fully operational systems. As noted previously many deployments covered in this study are relatively young (e.g. up to 5 years), making 42% of fully operational systems which have been functioning for up to 5 years. About the same percentage of ATCSs (42%) has been operational between 5 and 10 years. We almost did

not find any adaptive systems which were installed 10 or more years ago that are still fully operational but there is an exception where one of the ATCS deployments (constituting 3% of all covered systems) has been in operations for 25+ years. From these findings we can conclude that majority of the ATCS have been functional for less than 10 years with an average ATCS lifespan somewhere around 6-7 years. We believe that this average lifespan is too short and that institutional issues, more than outdated hardware and/or software, are the major barrier to achieve a longer lifespan for the ATCSs.

Table 13 Lifespan distribution of fully-operational ATCSs

Years in operation	Percentage of fully operational systems
up to 5	42
5 to 10	42
10 to 15	12
15 to 20	0
20 to 25	0
25 to 30	3

Let us now compare these findings with expectations of the relevant representatives of the surveyed agencies. Figure 41 below shows expected lifespans of the ATCSs as perceived by the agencies. The findings show that in 78% of the cases the agencies expected an ATCS to have a lifespan between 5 to 15 years, whereas 15% expects their systems to operate more than 15 years. Based on two sets of data it is easy to conclude that the expectations of the deploying agencies are a bit optimistic and that most of the deployed ATCSs do not function long enough to meet expectations of their deplorers. If we dig a bit deeper into the data to find out which agencies are non-believers (there is 6% of those who marked an expected lifespan of 5 years or less) we see that their ATCS systems may have been decommissioned due to the fact that they were not found compatible with agency's expectations and practice.
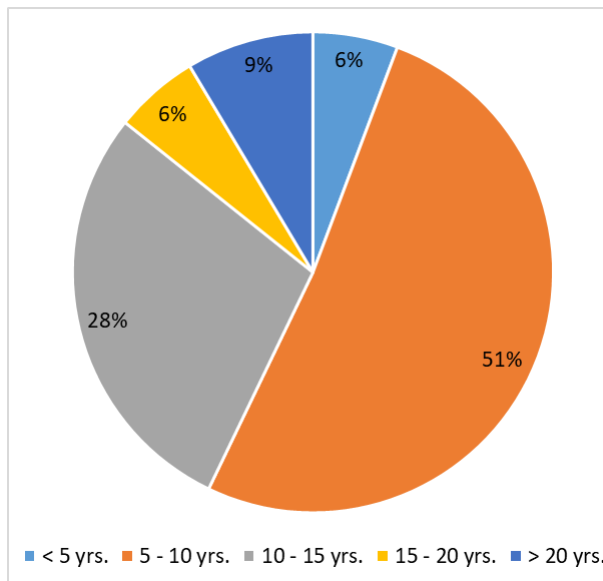
Figure 41 Expected ATCSs life span

Evaluation details

Assessing performance of a deployed ATCS represent an attempt to capture different values of performance measures for prevailing traffic demand on a network where the ATCS is installed. In order to document benefits of a deployed ATCS, a set of various performance measures is captured and compared

to the same type of performance measures captured while the ATCS was not functional. Depending on when and how the non-ATCS assessment was conducted, we recognize two evaluation methods for assessing ATCS performance: 1. "before-after" method and 2. "on-off" method.

In the "before-after" evaluation method, "before" study is done before an ATCS is installed in the field, usually while a conventional time-of-day (TOD) traffic signal control is operational. An "after" study is then performed once the ATCS is deployed with an adaptive regime replacing the TOD control. There is usually a several-month time span between 'before' and 'after' evaluation. Traffic conditions during 'before' and 'after' studies can significantly vary (especially if there are strong seasonal traffic fluctuations), thus making (sometimes) results of such comparative studies unfair. In the "on-off" evaluation method, both "on" and "off" studies are done after an ATCS is deployed in the field. In the case of "On" study the ATCS is turned on and the signals work in a (fully) adaptive mode. Logically, in the case of "Off" study the ATCS's adaptive operations are turned off and a set of background TOD plans (mimicking before ATCS conditions) controls the traffic. In the case of "on-off" study seasonal traffic variations can be avoided (if both studies are done within the same traffic season) but the issue could be made if the background TOD plans (working in "Off" study) are not identical to the true TOD plans, which were in effect before the ATCS was deployed.

The early ATCSs evaluation studies were conducted in the field regardless of the evaluation method, mainly depending on probe vehicle data and individual intersections observations. However, with the development of traffic simulation software packages, researchers have been able to simulate conventional and adaptive traffic control systems in virtual environment. Such ability provided an evaluation type which gives flexibility to evaluate ATCSs through numerous performance measures and numerous scenarios; thus, avoiding idiosyncrasies of field traffic conditions and the other uncontrollable factors. For this reason evaluations through simulation are also used as a valid method to investigate underlying performances of ATCSs and to better understand signal operations.

The surveyed data reports that out of 81 deployed ATCSs, 70 were evaluated. However, for 11 deployments results of evaluation studies were not entered in the (AT)2C database. The surveyed agencies simply did not make all of those studies available to the FAU research team in spite of the fact that multiple follow communications were sent. In addition to evaluations of deployed systems, evaluation studies of not-deployed systems (e.g., simulation evaluation studies that were performed in decision making process of ATCS deployment) were also entered in the database. Figure 42 shows overall numbers of conducted evaluation studies per each ATCS brand, and how many of those evaluations were included in this study and entered in the relevant (AT)2C database. In total, 85 results of evaluations out of 96 studies were obtained.
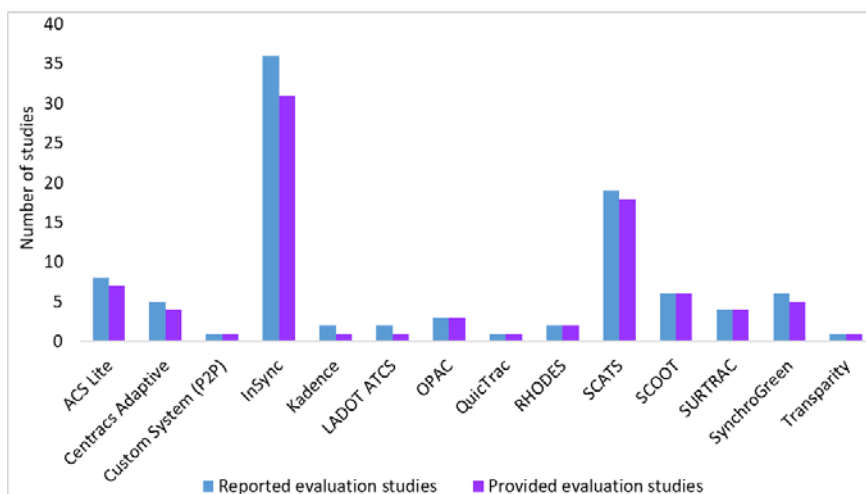
Figure 42 Conducted and provided evaluation studies per ATCS brand

System engineering (SE) process is an effective way for agencies interested in ATCS deployments to ensure that selected and deployed ATCSs meet their expectations and operational objectives. Actually, if an ATCS deployment is supported by federal financial aids it may be necessary to perform an SE process to secure access to such financial support (Fehon et al., 2012). Thus, it is interesting to find out how many of the deployed ATCSs were preceded by a relevant SE process. Table 14 shows that around one third of all of the deployed systems were preceded by a SE process whereas one half (56%) did not provide a definitive answer. In 9% of cases SE process was not applied.

Table 14 Deployments of ATCS preceded by the system engineering process

System engineering process conducted	% of deployments
Yes	36
No	9
Answer not provided	56

Another thing which is interesting to find out is who the entity that initialized the ATCS evaluation study is. In some cases such evaluations may be attached to the SE process and thus initiated by the procuring agency. Other times it will be a consulting company who performs the SE process or just happens to be interested to offer such services. As Figure 43 shows some other entities can also initiate an ATCS evaluation. The findings from Figure 43 shows in most of the cases it was a deploying agency but we also see a variety of other entities including research institutes, consultants, universities, etc.
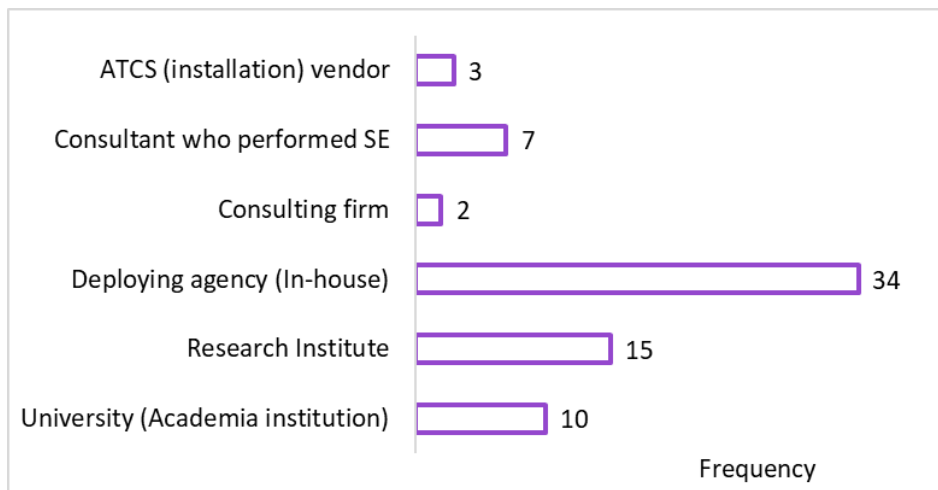
Figure 43 Distribution of initiators of the ATCSs evaluation studies

It is important to note that an entity that actually performs evaluation may be different from the entity which initiated the evaluation study. Based on obtained data it was found that in 45% of cases the entity that initiated an evaluation study was the one that, later, performed the evaluation study. Figure 44 shows how the evaluation studies are distributed among the various types of entities. The highest proportion of the evaluations was done by universities, consulting firms and research institutes. However, a good number of such studies was also performed, in-house, by the deploying agency.
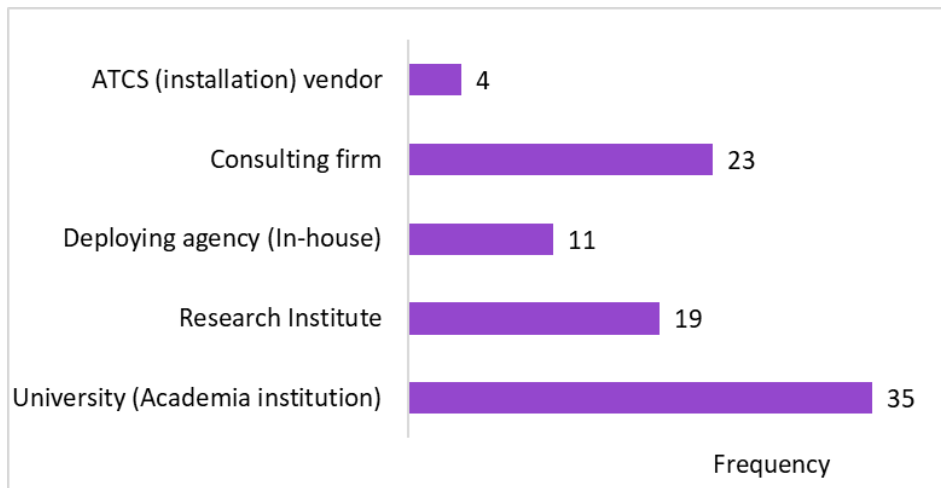
Figure 44 Frequency of entity types performing ATCS evaluations

Figure 45 (left) shows that in a slightly higher percentage traditional "before-after" over "on-off" evaluation studies were conducted. Similarly, as shown in the right side of Figure 45, the true field evaluations are much more preferable than the simulation studies, which were conducted in 25% of the cases. These findings are reasonable considering that good percent of evaluations was performed by universities and research institutes. It is also understandable why the agencies prefer field over simulation studies – simulation modeling is expensive and still lacks confidence of the agencies that may not be very familiar with the modeling processes. In addition, many agencies decided not to conduct true (officially contracted) evaluation studies but decided to do short in-house evaluations, where they would 'closely' monitor deployed system and do few ad-hoc field data collections (e.g. running few cars up and down' the corridor with the ATCS technology). The literature review shows that some evaluations were conducted in a manner where multiple signal timing plans were retrieved from adaptive traffic control operations (e.g. by averaging signal timing parameters of adaptive control) and compared with a single TOD plan (representing a non-adaptive solutions). Such comparisons are usually conducted in common signal optimization tools (e.g., Synchro) and they are used to (widely) estimate benefits of adaptive control. Considering that this approach retroactively assess timings from adaptive control to create multiple conventional TOD plans the approach is defined/called as 'retroactive' and was performed in 2% cases (as shown in Figure 45 left).
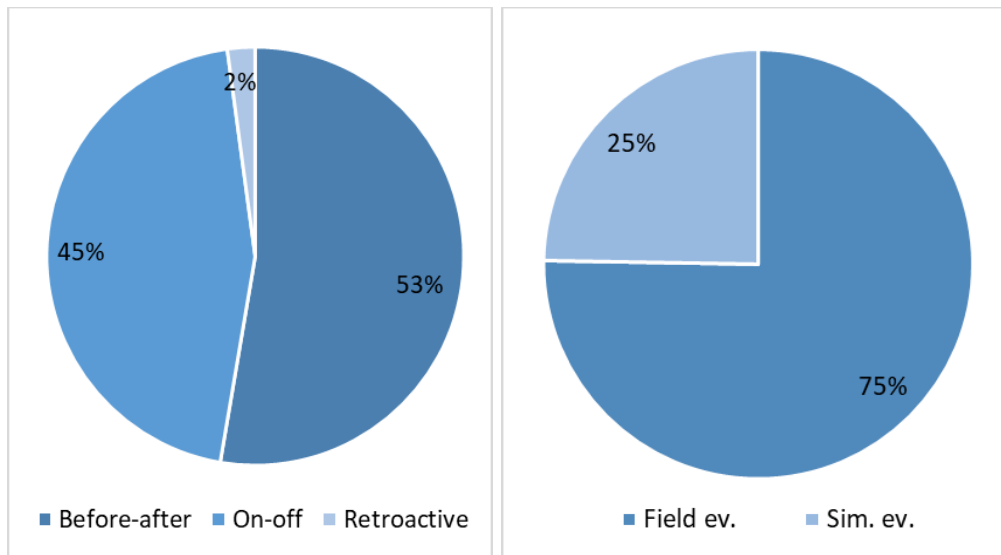
Figure 45 Frequency of evaluation types – control type (left) and data type (right)

Since most of the evaluation studies are conducted in the field it is interesting to see which of the hardware and software tools were used in the process of ATCSs evaluations. Figure 46 shows that in most of the evaluations, evaluators relied on the GPS technology, which is used to collect probe vehicles trajectories. When it comes to determining ATCSs impact on performance of the side-street traffic, evaluations of intersection delays were mostly performed by using the Jamar counting boards or by manual observations. In some cases, Bluetooth readers and wireless detectors were used to evaluate the travel times on the main corridors, but also video recordings were obtained from the cameras and post-processed to conduct intersection-level analysis.
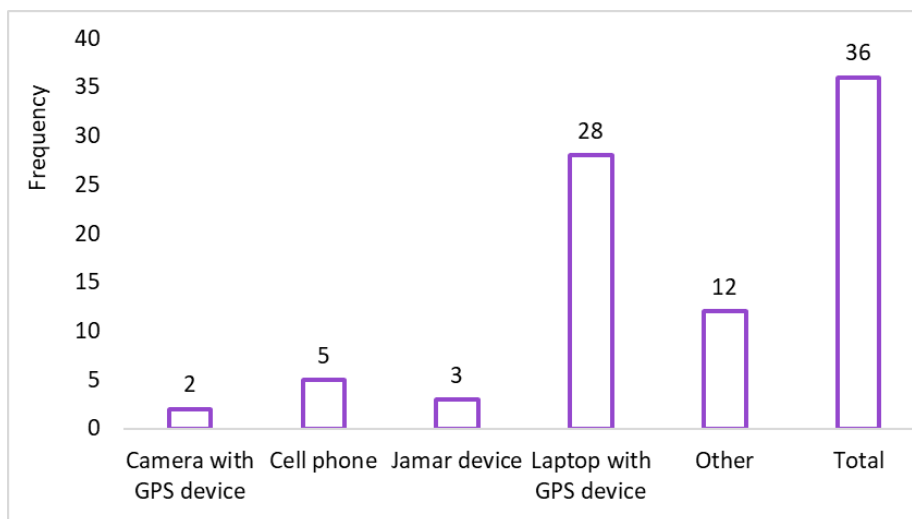
Figure 46 Frequency of data collection hardware used in evaluation studies

In addition to the hardware used for data collection, various software packages have been used for data processing and reduction. As shown in Figure 47, the PC travel and GPS Kit Pro are the main software tools utilized for most of the evaluations. These tools were mostly used to process vehicle trajectories collected from the GPS devices and retrieve perormance mesures such as delays, number of stops, travel

times, and estimated vehicle consumptions and emissions. The Tru-traffic is also one of the tools used to assess delay and travel time on the examined network, before and after the ATCS installation.
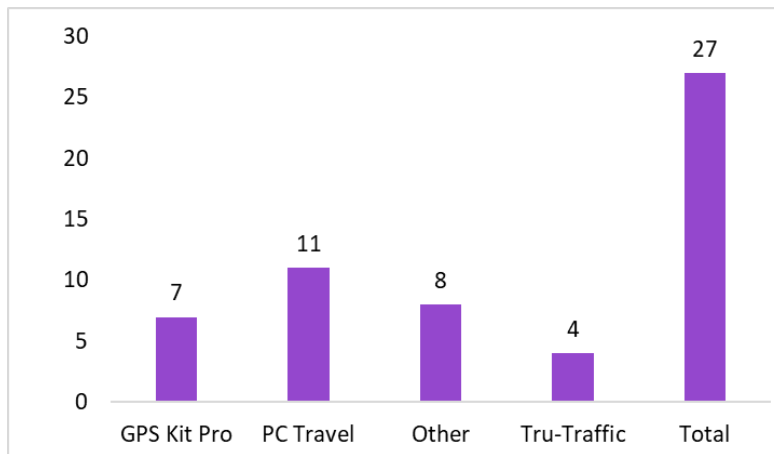
Figure 47 Frequency of software used in evaluation studies

The remaining 25% of evaluation studies were conducted in a simulation environment. Use of particular simulation tool in most of the cases will depend on avaliable interface between ATCS and tool iteself. In some instances tools wereused to mimic operations of ATCSs when direct access to a field-like ATCS interface was not in place. However, this approach should be taken with caution because it may give very unreliable results. Figure 48 shows that in most of the evaluations (55%) VISSIM was used to simulate ATCS operations, followed by CORSIM (18%) and Paramics (9%).
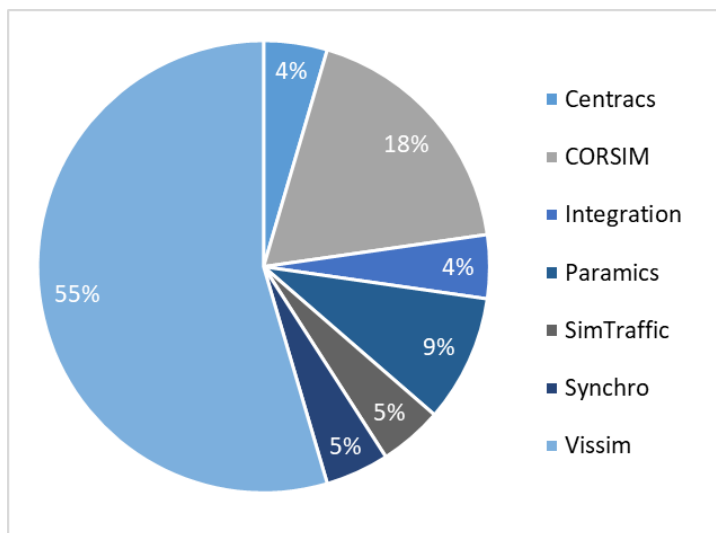
Figure 48 Frequency of various simulation tools used for evaluation

Data filtering

As previosly mentioned, the (AT)2C is developed in such a way to enable users to perform various database queries by using predefined filters. Results of such queries (selections through filtering) can be observed on the interactive dashboards, whose visual aids are updated every time a user modifies filtering options. The purpose of this chapter is to provide user an illustration on what type of results can be obtained from the (AT)2C. Since each evaluation study is characterized by number of categories (defined in the

framework of this study) it is hard to purely isolate effects of particular category on overall ATCS performance. In the following text, summary of data filtering is presented in the tabular forms where all available results of evaluations are averaged for particular period charaterized with standard deviation. This type of aggregation (averaging) is important to note considering that it may hide/diminish effects of particular ATCS deployment and its performance measures. For that reason, following tables should be used carefully and more to identfy trends of ATCS success than to make judgements about particular evaluations. A user should be reminded that while filtering is used to provide overall statistics, the user can observe each evaluation study separately to find any information of particular interest for that study.

This approach can provide a user with an opportunity to analyze various ATCS deployments through observation of performance measures, which will be modified based on the filtering selections that an (AT)2C user makes. Thus, one can observe changes in the performance measures for each evaluation study that results from changing any combination of the ATCS data categories (e.g. agency type, network jurisdiction, annual budget for capital traffic-related project, signal operations and maintenance, number of deploying ATCSs, number of signals under agency jurisdiction, and others) by selecting proper filtering options. It is important to note here that for each ATCS deployment there are usually more than 74 data categories identified in the framework this study. However, in order to make the (AT)2C a practical tool (e.g. intuitive and easy to use), 33 most important categories (that characterize an ATCS deployment and evaluation) were given to users to 'play with'. In the cases of missing data (e.g. for certain deployments and evelution studies data were not reported), such database fields were left blank.

The evaluation results herein are organized in the following manner: for each examined period (i.e., AM peak period, mid-day peak period, PM peak period, Friday PM peak hour (i.e. special event), average Saturday, and average weekday each performance measure adressing vehicular traffic seen through efficiency (i.e., delay, travel times, split failure, etc.) and environmental imapct (i.e., fuel consumption, emissions, etc.) is entered in the database, if it was provided in the evaluation study or reported in the survey. Morover, since an evaluation study can provide results on so many different spatial levels (e.g. per movement, per intersection, per route, for the entire network) it was decided to limit coverage of the results to only two major levels: 1. performance of deployed ATCS on individual route(s), and/or 2. network performance.

Table 15 shows an example of reporting performance measures for these two levels (routes and network). Considering that not every evaluation study provides results for every possible evalution period and the same set of performance measurs, whenever some of the values were not available this was denoted with an "NR". Cases where a performance measure is worse after an ATCS deployment than before are given as positive values.

Table 15 Overall performance measures reductions [%] for all ATCS brands

Impact Type		Efficiency impact												Environmental impact								
Performance measure		Travel time		Delay		Split failure	Number of stops		Side street delay	Queue length	Side street split failure	Tranist travel time	Number of crashes	Number of conflicts	Fuel consumption		Emissions - HC		Emissions - CO		Emissions - NOx		Emissions - All polutants
Time Period		Routes based	Network level	Routes based	Network level	Network level	Routes based	Network level	Routes based	Routes based	Network level	Network level	Network level	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Network level
AM peak hour	Average	-10.3	-13.1	-27.6	-13.6	NR	-27.4	-13.4	11.7	NR	NR	-3.8	NR	-5.9	-9.6	-1.5	-13.5	-1.6	-7.3	-1.6	-7.9	-3.3	-0.2
	STD	14.4	11.9	29.8	20.0	NR	35.5	12.2	22.8	NR	NR	0.0	NR	0.0	8.8	2.0	11.1	1.8	4.9	1.7	4.0	2.4	0.0
Mid-day peak hour	Average	-10.9	-14.5	-24.5	-17.5	NR	-32.9	-19.4	13.9	NR	NR	-4.6	-22.3	-8.4	-16.0	0.0	-26.7	-4.9	-14.0	-2.9	-15.1	-4.7	-0.3
	STD	10.6	12.2	45.5	19.4	NR	25.6	23.6	22.5	NR	NR	0.0	0.0	0.0	21.0	0.0	25.3	5.0	10.7	3.0	9.6	4.7	0.0
PM peak hour	Average	-9.5	-6.4	-23.7	-11.3	NR	-25.2	-6.2	-3.4	-12.0	NR	-2.6	-14.0	-8.5	-4.1	-1.0	-8.3	-4.2	-8.2	-2.6	-6.6	-7.8	NR
	STD	13.7	13.3	29.1	20.6	NR	27.7	12.9	32.9	6.6	NR	0.0	5.3	3.8	4.3	1.1	10.0	4.3	2.0	2.2	2.4	9.5	NR
Friday PM Peak Hour	Average	-14.5	-14.6	-12.6	-14.9	NR	-8.0	8.6	-3.5	-22.1	NR	NR	NR	NR	-2.2	3.5	-1.1	3.9	0.5	6.9	-0.7	1.9	NR
	STD	6.5	8.1	24.9	15.3	NR	47.4	18.0	0.0	0.4	NR	NR	NR	NR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NR
Average Saturday	Average	-10.3	NR	-30.9	-20.4	NR	-15.0	NR	NR	NR	NR	NR	NR	NR	-3.3	NR	-4.7	NR	-2.8	NR	-5.4	NR	NR
	STD	5.8	NR	15.1	0.0	NR	8.5	NR	NR	NR	NR	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR	NR
Average weekday	Average	-6.1	NR	-7.1	-1.0	-85.5	NR	NR	-1.6	NR	-11.0	-0.3	-69.0	NR	NR	-2.5	-4.5	NR	-3.0	NR	-2.5	NR	NR
	STD	2.4	NR	7.0	0.3	0.0	NR	NR	0.3	NR	0.0	0.0	0.0	NR	NR	0.5	4.5	NR	1.0	NR	1.5	NR	NR
All periods	Average	-10.3	-12.2	-21.1	-13.1	-85.5	-21.7	-7.6	3.4	-17.0	-11.0	-2.8	-35.1	-7.6	-7.0	-0.3	-9.8	-1.7	-5.8	-0.1	-6.4	-3.4	-0.3
	STD	8.9	11.4	25.2	12.6	0.0	29.0	4.1	15.7	3.5	0.0	0.0	1.8	1.3	6.8	0.7	8.5	2.8	3.1	1.7	2.9	4.1	0.0

Generally, based on the obtained evaluation studies, one can conclude that the evaluated ATCSs did bring improvement in various traffic performance measures, for regular (i.e., typical weekday, Mon-Thu) and oversaturated traffic conditions (i.e., Friday PM peak hour, during special event) in most of the cases. In a very few cases (e.g. for Friday PM peak hour) number of stops, reported on a network level, were

slightly worse after an ATCS was deployed. However, these can be considered as exemptions which do not change the generally positive picture about ATCS performance. Similarly, it is shown that transit travel times were reduced by 2.8% on average for all periods. In terms of environmental impacts, average fuel reduction (for all periods) was in a range 0.3% - 7%, emission pollutants were also decreased in a range from 0.1% - 9.8%. Finally, it was reported that the number of crashes was reduced by 35.1%. When number of conflicts were analyzed decrease of 7.6% was reported.

To provide an example of filtering that can be performed with the (AT)2C, we display below several tables which show evaluation results filtered for a number of specific ATCS brands. Tables 16-19 confirm what was stated above – in most of the cases these ATCS deployments have resulted in improved performance of traffic conditions in their relevant networks.

Table 16 Performance improvements [%] for deployments of Centracs Adaptive

Impact Type		Efficiency impact		
Performance measure		Travel time	Delay	
Time Period		Network level	Routes based	Network level
AM peak hour	Average	-4.0	17.0	-5.5
	STD	0.0	0.0	0.0
Mid-day peak hour	Average	-8.0	-1.4	-5.8
	STD	0.0	0.0	0.0
PM peak hour	Average	-4.0	-17.6	-2.5
	STD	0.0	0.0	0.0
Friday PM Peak Hour	Average	NR	NR	NR
	STD	NR	NR	NR
Average Saturday	Average	NR	NR	NR
	STD	NR	NR	NR
Average weekday	Average	NR	NR	NR
	STD	NR	NR	NR
All periods	Average	-5.3	-0.7	-4.6
	STD	0.0	0.0	0.0

Table 17 Performance improvements [%] for deployments of InSync

Impact Type		Efficiency impact								Environmental impact									
Performance measure		Travel time		Delay		Number of stops		Side street delay	Queue length	Number of crashes	Number of conflicts	Fuel consumption		Emissions - HC		Emissions - CO		Emissions - NOx	
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Routes based	Network level	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level
AM peak hour	Average	-14.3	-23.8	-45.3	6.4	-34.7	-11.8	-2.1	NR	NR	-5.9	-21.1	-3.4	-28.9	-2.5	-13.3	-2.5	-13.2	-4.9
	STD	3.2	0.0	24.4	0.0	23.9	0.0	3.6	NR	NR	0.0	5.4	0.0	0.0	1.2	0.0	1.2	0.0	0.1
Mid-day peak hour	Average	-13.4	NR	-33.2	NR	-37.6	-5.8	-4.4	NR	NR	-8.4	-45.4	NR	-67.9	-9.9	-24.1	-5.9	-24.1	-9.3
	STD	9.9	NR	63.3	NR	26.9	0.0	0.0	NR	NR	0.0	17.3	NR	0.0	0.0	0.0	0.0	0.0	0.0
PM peak hour	Average	-12.0	NR	-34.0	NR	-29.3	-7.3	NR	-18.9	-17.0	-5.9	-9.6	NR	-22.4	-10.0	-9.7	-5.4	-9.6	-21.1
	STD	16.1	NR	38.2	NR	28.5	0.0	NR	2.2	3.1	3.1	0.0	NR	0.0	0.0	0.0	0.0	0.0	0.0
Friday PM Peak Hour	Average	-17.8	NR	-33.5	NR	-57.4	-9.4	-3.5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	1.0	NR	1.5	NR	0.0	0.0	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	-11.0	NR	-37.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	0.0	NR	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average	-9.0	NR	-13.0	NR	NR	NR	NR	NR	NR	NR	NR	-3.0	-9.0	NR	-4.0	NR	-4.0	NR
	STD	0.0	NR	0.0	NR	NR	NR	NR	NR	NR	NR	NR	0.0	0.0	NR	0.0	NR	0.0	NR
All periods	Average	-12.9	-23.8	-32.7	6.4	-39.7	-8.6	-3.3	-18.9	-17.0	-6.7	-25.4	-3.2	-32.0	-7.5	-12.8	-4.6	-12.7	-11.8
	STD	5.0	0.0	21.2	0.0	19.8	0.0	1.2	2.2	3.1	1.0	7.6	0.0	0.0	0.4	0.0	0.4	0.0	0.0

Table 18 Performance improvements [%] for deployments of SCATS

Impact Type		Efficiency impact									Environmental impact								
Performance measure		Travel time		Delay		Number of stops		Side street delay	Queue length	Tranist travel time	Number of crashes	Number of conflicts	Fuel consumption		Emissions - HC		Emissions - CO		Emissions - NOx	
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Routes based	Network level	Network level	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level
AM peak hour	Average	1.2	NR	-14.3	NR	23.3	NR	NR	NR	NR	NR	NR	-6.7	NR	-3.5	NR	-1.3	NR	-3.5	NR
	STD	18.1	NR	3.8	NR	55.0	NR	NR	NR	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR
Mid-day peak hour	Average	-9.0	NR	-16.9	NR	-25.8	NR	NR	NR	NR	-22.3	NR	-3.8	NR	-6.0	NR	-3.3	NR	-5.6	NR
	STD	7.6	NR	9.2	NR	5.1	NR	NR	NR	NR	0.0	NR	0.8	NR	0.3	NR	0.9	NR	1.8	NR
PM peak hour	Average	-7.6	-5.4	-14.3	-9.2	-4.8	-7.9	-45.1	-2.5	NR	NR	-11.7	-5.6	-2.0	-0.8	-2.6	-6.4	-2.4	-5.9	-2.1
	STD	4.2	18.4	17.3	28.9	28.9	14.0	0.0	0.0	NR	NR	0.0	0.7	0.0	0.8	0.0	0.8	0.0	1.9	0.0
Friday PM Peak Hour	Average	-3.3	NR	8.3	4.1	16.7	26.6	NR	NR	NR	NR	NR	-2.2	3.5	-1.1	3.9	0.5	6.9	-0.7	1.9
	STD	0.0	NR	15.6	0.0	32.1	0.0	NR	NR	NR	NR	NR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average Saturday	Average	-5.6	NR	-21.2	NR	-15.2	NR	NR	NR	NR	NR	NR	-3.3	NR	-4.7	NR	-2.8	NR	-5.4	NR
	STD	3.0	NR	8.5	NR	8.5	NR	NR	NR	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR
Average weekday	Average	NR	NR	NR	-0.6	NR	NR	NR	NR	-0.3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	0.0	NR	NR	NR	NR	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
All periods	Average	-4.9	-5.4	-11.7	-1.9	-1.2	9.4	-45.1	-2.5	-0.3	-22.3	-11.7	-4.3	0.7	-3.2	0.7	-2.7	2.3	-4.2	-0.1
	STD	6.6	18.4	10.9	9.6	25.9	7.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	1.2	0.0	0.3	0.0	0.7	0.0

Table 19 Performance improvements [%] for deployments of SynchroGreen

Impact Type		Efficiency impact						Environmental impact				
Performance measure		Travel time	Delay	Number of stops	Side street delay	Queue length	Number of crashes	Number of conflicts	Fuel consumption	Emissions - HC	Emissions - CO	Emissions - NOx
Time Period		Routes based	Routes based	Routes based	Routes based	Routes based	Network level	Network level	Routes based	Routes based	Routes based	Routes based
AM peak hour	Average	8.6	-4.5	-24.5	6.0	NR	NR	NR	-9.5	-8.0	-7.2	-7.0
	STD	14.0	5.7	0.0	0.0	NR	NR	NR	0.0	0.0	0.0	0.0
Mid-day peak hour	Average	-5.0	-26.4	-34.9	NR	NR	NR	NR	-21.4	-26.7	-25.4	-25.0
	STD	13.3	11.5	0.0	NR	NR	NR	NR	0.0	0.0	0.0	0.0
PM peak hour	Average	4.0	-15.0	-18.1	NR	-7.7	-7.9	-10.4	-5.2	-9.3	-10.4	-5.2
	STD	9.2	2.1	0.0	NR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Friday PM Peak Hour	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average	-3.2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
All periods	Average	1.1	-15.3	-25.8	6.0	-7.7	-7.9	-10.4	-12.0	-14.7	-14.4	-12.4
	STD	9.1	6.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Another aspect of looking at effectiveness of the ATCSs could be to categorize benefits of ATCSs based on their AADTs on the busiest roads within the ATCS deployment. Those AADTs can fall within one of the three groups: relatively low (≤ 35,000), moderate (35,000-45,000) and high (≥55,000). Tables 20, 21 and 22 shows such results, generated by applying proper filters in the (AT)2C. For relatively low AADT values, benefits were reported for all performance measures except for side streets where this measure was negligibly increased. A similar trend is observed for the other AADT levels. Interestingly, when moderate and high AADTs (for all periods) are compared, one can observe that higher benefits were achieved for moderate traffic conditions (for all of the efficiency-based traffic performance measures). This is in line with general understanding that ATCSs work better in moderate traffic conditions than if traffic approaches saturation. When 'environmental' performance measures are examined it can be seen that benefits are not so conclusive for either AADT group. In the cases with relatively low AADTs, when performances are compared with any other group of AADTs (i.e., moderate, high), results are not consistent.

Table 20 Performance reductions [%] for all ATCSs with AADT ≤ 35,000

Performance measure		Travel time		Delay		Number of stops		Side street delay		Transit travel time		Number of crashes	Number of conflicts	Fuel consumption		Emissions - HC		Emissions - CO		Emissions - NOx		Emissions - All polutants
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Network level	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Network level
AM peak hour	Average	-12.4	-14.4	-42.7	-23.0	-31.3	-14.2	0.3			-3.8	NR	NR	-6.7	0.5	-3.5	-1.9	-1.3	-2.0	-3.5	-2.5	-0.2
	STD	20.7	12.8	22.8	17.9	23.8	12.2	0.0			0.0	NR	NR	0.0	0.0	0.0	1.7	0.0	1.7	0.0	2.1	0.0
Mid-day peak hour	Average	-11.7	-16.4	-43.5	-21.4	-30.0	-26.2	0.4			-4.6	NR	NR	-4.8	0.0	-6.5	-4.9	-4.5	-2.9	-3.4	-4.7	-0.3
	STD	9.8	13.4	23.2	18.2	24.5	21.5	0.0			0.0	NR	NR	0.0	0.0	0.0	4.1	0.0	2.4	0.0	3.8	0.0
PM peak hour	Average	-13.7	-0.5	-27.2	-9.7	-30.0	-12.6	1.8			-2.6	NR	-11.7	-4.8	-1.0	5.9	-4.2	-5.5	-2.6	-3.6	-7.8	NR
	STD	9.3	0.7	8.9	6.8	23.4	8.6	0.0			0.0	NR	0.0	0.0	0.9	0.0	3.7	0.0	1.9	0.0	8.2	NR
Friday PM Peak Hour	Average	NR	NR	NR	NR	NR	NR	NR			NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR			NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	-10.7	NR	-34.7	-20.4	-5.8	NR	NR			NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	6.0	NR	14.5	0.0	0.0	NR	NR			NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average	-7.5	NR	-14.0	NR	NR	NR	NR			NR	-69.0	NR	NR	-2.5	NR	-3.0	NR	-2.5	NR	-2.5	NR
	STD	1.2	NR	0.8	NR	NR	NR	NR			NR	0.0	NR	NR	0.4	NR	3.7	NR	0.8	NR	1.2	NR
All periods	Average	-11.2	-10.4	-32.4	-18.6	-24.3	-17.7	0.8			-3.7	-69.0	-11.7	-5.4	-0.7	-2.1	-3.7	-3.6	-2.5	-3.3	-5.0	-0.3
	STD	9.4	9.0	14.1	10.7	17.9	4.9	0.0			0.0	0.0	0.0	0.0	0.3	0.9	3.2	0.2	2.0	0.3	4.7	0.0

Table 21 Performance reductions [%] for all ATCSs with AADT 35,000 – 55,000

Time Period	Stat	Travel time Routes based	Travel time Network level	Delay Routes based	Delay Network level	Split failure Network level	Number of stops Routes based	Number of stops Network level	Side street delay Routes based	Queue length Routes based	Side street split failure Network level	Transit travel time Network level	Number of crashes Network level	Number of conflicts Network level	Fuel consumption Routes based	Fuel consumption Network level	Emissions - HC Routes based	Emissions - HC Network level	Emissions - CO Routes based	Emissions - CO Network level	Emissions - NOx Routes based	Emissions - NOx Network level
AM peak hour	Average	-13.7	-13.9	-30.4	0.5	NR	-35.7	-11.8	0.6	NR	NR	NR	NR	-5.9	-21.1	-3.4	-28.9	-1.0	-13.3	-1.0	-13.2	-4.8
	STD	NR	8.1	29.6	4.9	NR	22.0	0.0	4.5	NR	NR	NR	NR	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mid-day peak hour	Average	-12.3	-8.0	-35.1	-5.8	NR	-48.0	-5.8	-4.4	NR	NR	NR	-22.3	-8.4	-31.2	NR	-36.8	NR	-13.2	NR	-16.0	0.0
	STD	9.4	0.0	29.6	0.0	NR	21.5	0.0	0.0	NR	NR	NR	0.0	0.0	23.0	NR	25.4	NR	8.9	NR	6.6	NR
PM peak hour	Average	-11.3	-16.8	-24.7	-25.8	NR	-29.5	-7.3	-30.5	-14.8	NR	NR	-20.8	-5.9	-8.1	NR	-15.0	NR	-8.5	NR	-8.9	NR
	STD	15.2	7.4	32.0	13.9	NR	27.0	0.0	11.9	6.6	NR	NR	0.0	3.1	1.3	NR	6.0	NR	0.9	NR	0.6	NR
Friday PM Peak Hour	Average	-13.0	-22.0	-26.0	-27.4	NR	-39.9	-9.4	-3.5	-22.5	NR	NR	NR	NR	-2.2	NR	-1.1	NR	0.5	NR	-0.7	NR
	STD	6.0	0.0	9.3	0.0	NR	14.2	0.0	0.0	0.0	NR	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR
Average Saturday	Average	-7.4	NR	-25.2	NR	NR	-20.0	NR	NR	NR	NR	NR	NR	NR	-3.3	NR	-4.7	NR	-2.8	NR	-5.4	NR
	STD	2.9	NR	9.9	NR	NR	8.8	NR	NR	NR	NR	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR
Average weekday	Average	NR	NR	NR	NR	-85.5	NR	NR	NR	NR	-11.0	-0.3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	0.0	NR	NR	NR	NR	0.0	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
All periods	Average	-11.5	-15.2	-28.3	-14.6	-85.5	-34.6	-8.6	-9.4	-18.7	-11.0	-0.3	-21.6	-6.7	-13.2	-3.4	-17.3	-1.0	-7.5	-1.0	-8.8	-2.4
	STD	8.4	3.9	22.1	4.7	0.0	18.7	0.0	4.1	3.3	0.0	0.0	0.0	1.0	5.9	0.0	6.3	0.0	2.0	0.0	1.4	0.0

Table 22 Performance reductions [%] for all ATCSs with AADT ≥ 55,000

Time Period	Stat	Travel time Routes based	Travel time Network level	Delay Routes based	Delay Network level	Number of stops Routes based	Queue length Routes based	Number of crashes Network level	Number of conflicts Network level	Fuel consumption Routes based	Fuel consumption Network level	Emissions - HC Routes based	Emissions - HC Network level	Emissions - CO Routes based	Emissions - CO Network level	Emissions - NOx Routes based	Emissions - NOx Network level
AM peak hour	Average	-8.5	NR	-11.5	NR	-24.5	NR	NR	NR	-9.5	NR	-8.0	NR	-7.2	NR	-7.0	NR
	STD	3.9	NR	0.0	NR	0.0	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR
Mid-day peak hour	Average	-11.9	NR	-40.5	NR	-34.9	NR	NR	NR	-21.4	NR	-26.7	NR	-25.4	NR	-25.0	NR
	STD	9.2	NR	0.0	NR	0.0	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR
PM peak hour	Average	-11.0	8.7	-17.6	11.8	-18.1	-5.7	-7.9	-10.4	-5.2	NR	-9.3	NR	-10.4	NR	-5.2	NR
	STD	7.8	14.4	0.0	31.2	0.0	1.6	0.0	0.0	0.0	NR	0.0	NR	0.0	NR	0.0	NR
Friday PM Peak Hour	Average	NR	-18.5	NR	-32.2	NR	-21.6	NR	NR	NR	3.5	NR	3.9	NR	6.9	NR	1.9
	STD	NR	0.0	NR	0.0	NR	0.0	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0
Average Saturday	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
All periods	Average	-10.5	-4.9	-23.2	-10.2	-25.8	-13.7	-7.9	-10.4	-12.0	3.5	-14.7	3.9	-14.4	6.9	-12.4	1.9
	STD	7.0	7.2	0.0	15.6	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

As stated previously, there is a notion that the magnitude of benefits from an ATCS deployment may depend on the conditions of traffic signal control which was in effect before the ATCS has been deployed. Thus, it is more likely that more frequently retimed signals will result in better performance thus deeming the post-installation ATCS performance less beneficial (than if a more-neglected signals were functional before the ATCS deployment). Performance measures retrieved under these assumption (and relevant filtering selections) are shown in Tables 23, 24 and 25. Signals that are retimed every year or more frequently are considered as frequently retimed signals. In cases where signals are retimed every one to two years they are considered to be moderately frequently retimed (Table 24), and finally if they are retimed every three years or longer, they are considered to be rarely retimed (Table 25). Based on the reported benefits (for all periods considered), when high and moderately frequently retimed signals are compared with each other, higher benefits were achieved for moderately retimed signals. This finding aligns with general perception that if ATCSs are installed on a network where signals are not retimed with high frequency the benefits of such installation will be higher than of those where traditional (e.g. coordinated-actuated) signals are retimed very frequently. In cases of a low frequency of retimed signals, results were not consistent.

Table 23 Performance improvements [%] for frequently retimed pre-ATCS networks

Impact Type		Efficiency impact					
Performance measure		Travel time		Delay		Number of stops	Queue length
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Routes based
AM peak hour	Average	-17.6	-4.0	-39.7	-5.5	-48.7	NR
	STD	0.0	0.0	34.8	0.0	18.6	NR
Mid-day peak hour	Average	-13.3	-8.0	-41.4	-5.8	-36.5	NR
	STD	3.7	0.0	25.7	0.0	21.6	NR
PM peak hour	Average	-11.6	-9.1	-29.9	-16.1	-15.2	-9.7
	STD	1.5	4.2	7.6	8.0	12.4	4.1
Friday PM Peak Hour	Average	NR	-20.3	NR	-29.8	NR	-22.1
	STD	NR	1.4	NR	2.0	NR	0.4
Average Saturday	Average	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR
Average weekday	Average	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR
All periods	Average	-14.2	-10.3	-37.0	-14.3	-33.4	-15.9
	STD	1.8	1.4	22.7	2.5	17.5	2.2

Table 24 Performance improvements [%] for moderately retimed pre-ATCS networks

Impact Type		Efficiency impact						Environmental impact
Performance measure		Travel time		Delay		Number of stops		Emissions - All polutants
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Network level	Network level
AM peak hour	Average	-18.5	-30.1	-74.6	-47.8	-50.4	-29.1	-0.2
	STD	13.9	0.0	0.0	0.0	12.9	0.0	0.0
Mid-day peak hour	Average	-3.1	-32.8	NR	-49.8	-51.0	-52.6	-0.3
	STD	0.0	0.0	NR	0.0	0.0	0.0	0.0
PM peak hour	Average	-19.9	NR	-79.1	NR	-41.3	NR	NR
	STD	18.3	NR	0.0	NR	33.7	NR	NR
Friday PM Peak Hour	Average	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR
All periods	Average	-13.9	-31.5	-76.9	-48.8	-47.6	-40.9	-0.3
	STD	10.7	0.0	0.0	0.0	15.5	0.0	0.0

Table 25 Performance improvements [%] for rarely retimed pre-ATCS networks

Impact Type		Efficiency impact			
Performance measure		Travel time	Delay		Number of stops
Time Period		Routes based	Routes based	Network level	Routes based
AM peak hour	Average	-7.2	-8.4	NR	-15.1
	STD	8.1	18.3	NR	20.9
Mid-day peak hour	Average	-15.2	-22.0	NR	-32.1
	STD	6.3	9.7	NR	0.0
PM peak hour	Average	-10.0	-18.6	-18.8	-32.1
	STD	8.7	14.0	0.0	6.0
Friday PM Peak Hour	Average	-19.1	NR	NR	NR
	STD	0.0	NR	NR	NR
Average Saturday	Average	-10.4	-35.1	NR	-11.1
	STD	0.0	0.0	NR	0.0
Average weekday	Average	NR	NR	NR	NR
	STD	NR	NR	NR	NR
All periods	Average	-12.4	-21.0	-18.8	-22.6
	STD	4.6	10.5	0.0	6.7

Type of traffic signal control for pre-ATCS conditions is another aspect to look at the ATCS operational benefits. There are essentially two types of pre-ATCSs signal control operations, actuated (semi or fully) and non-actuated (fixed). For each of these types of pre-ATCS control operational benefits from ATCSs are summarized and presented in Tables 26-28.

For fully-actuated pre-ATCS signal control type, as shown in Table 26, it is found that (during almost all of the evaluated periods) most of the performance measures are improved. However, negligible increase in reported delay on network level were noted for AM peak and Friday PM peak periods. In addition, during Friday PM peak hour number of stops were increased (26%). However, it needs to be stated that this result, for number of stops on Friday PM peak hour, is based only on a single evaluated system.

Table 26 Performance reduction [%] for pre-ATCS fully-actuated networks

Impact Type		Efficiency impact												Environmental impact							
Performance measure		Travel time		Delay		Split failure	Number of stops		Side street delay	Queue length	Side street split failure	Number of crashes	Number of conflicts	Fuel consumption		Emissions - HC		Emissions - CO		Emissions - NOx	
Time Period		Routes based	Network level	Routes based	Network level	Network level	Routes based	Network level	Routes based	Routes based	Network level	Network level	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level
AM peak hour	Average	-13.3	-13.9	-35.5	0.5	NR	-40.5	NR	4.2	NR	NR	NR	NR	-11.1	NR	-13.5	NR	-7.3	NR	-7.9	NR
	STD	NR	8.1	28.8	4.9	NR	17.1	NR	1.5	NR	NR	NR	NR	7.9	NR	9.6	NR	4.2	NR	3.5	NR
Mid-day peak hour	Average	-11.5	-8.0	-41.5	-5.8	NR	-37.3	NR	NR	NR	NR	NR	NR	-20.9	NR	-33.7	NR	-18.0	NR	-17.5	NR
	STD	11.0	0.0	27.6	0.0	NR	29.1	NR	NR	NR	NR	NR	NR	20.5	NR	22.1	NR	8.3	NR	8.6	NR
PM peak hour	Average	-10.6	-4.3	-22.3	-8.4	NR	-20.3	-7.9	-30.5	-13.4	NR	-14.0	-10.6	-5.6	-2.0	-8.6	-2.6	-8.5	-2.4	-6.1	-2.1
	STD	15.0	15.6	30.8	24.6	NR	31.7	14.0	11.9	6.6	NR	4.6	0.7	1.9	0.0	10.0	0.0	1.9	0.0	2.2	0.0
Friday PM Peak Hour	Average	-19.1	-3.3	-2.1	0.1	NR	-0.7	26.6	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	0.0	0.0	24.1	3.2	NR	46.3	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	-11.0	NR	-37.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	0.0	NR	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average	-6.1	NR	-6.2	-1.2	-85.5	NR	NR	-1.9	NR	-11.0	NR	NR	NR	-3.0	-9.0	NR	-4.0	NR	-4.0	NR
	STD	2.4	NR	5.6	0.0	0.0	NR	NR	0.0	NR	0.0	NR	NR	NR	0.0	0.0	NR	0.0	NR	0.0	NR
All periods	Average	-11.9	-7.4	-24.1	-3.0	-85.5	-24.7	9.4	-9.4	-13.4	-11.0	-14.0	-10.6	-12.5	-2.5	-16.2	-2.6	-9.5	-2.4	-8.9	-2.1
	STD	5.7	5.9	19.5	6.5	0.0	31.0	7.0	4.5	6.6	0.0	4.6	0.7	10.1	0.0	10.4	0.0	3.6	0.0	3.6	0.0

For semi-actuated pre-ATCS signal control type, as shown in Table 27, highest reduction was achieved (when all periods are considered) for routes-based delay and number of stops, 34.9% and 35.3%, respectively. More interestingly, if same values are compared for fully-actuated operations, it can be seen that lower benefits were reported: 24.1% and 24.7% for delay and number of stops, respectively. Based on such a comparison, it can be concluded that benefits of (evaluated) ATCSs tend to be higher in the cases where previous signal system was semi-actuated than when such a system was fully actuated. It should be noted here that 'fully actuated', as defined in our survey and analysis, does not exclude coordination or in

other words it does not mean 'free-running' signals. Instead, it means that all of the phases can be actuated as opposed to semi-actuated systems where major (usually coordinated phases) are not driven by detected demand. From that perspective, this finding makes sense as more actuation certainly (in most of the cases) leads to a better utilization of green time which then becomes a case that is more difficult to be improved by an ATCS deployment.

Table 27 Performance improvements [%] for pre-ATCS semi-actuated networks

Impact Type		Efficiency impact					Environmental impact			
Performance measure		Travel time		Delay		Number of stops	Fuel consumption	Emissions - HC	Emissions - CO	Emissions - NOx
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Routes based	Routes based
AM peak hour	Average	-2.8	-8.8	-41.5	NR	-39.5	NR	NR	NR	NR
	STD	7.9	0.0	0.0	NR	4.0	NR	NR	NR	NR
Mid-day peak hour	Average	-3.1	-17.2	NR	NR	-51.0	NR	NR	NR	NR
	STD	0.0	0.0	NR	NR	0.0	NR	NR	NR	NR
PM peak hour	Average	-3.8	-12.9	-29.1	-18.8	-15.5	NR	NR	NR	NR
	STD	5.3	0.0	0.0	0.0	9.5	NR	NR	NR	NR
Friday PM Peak Hour	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	-19.0	NR	-54.0	NR	NR	NR	NR	NR	NR
	STD	0.0	NR	0.0	NR	NR	NR	NR	NR	NR
Average weekday	Average	-6.0	NR	-15.0	-0.6	NR	-2.0	0.0	-2.0	-1.0
	STD	0.0	NR	0.0	0.0	NR	0.0	0.0	0.0	0.0
All periods	Average	-6.9	-13.0	-34.9	-9.7	-35.3	-2.0	0.0	-2.0	-1.0
	STD	2.6	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.0

In the cases where pre-ATCSs type of control was based on fixed-time TOD plans, it was found that delay and number of stops were reduced by 16.6 to 20.0%, as shown in Table 28. The same set of performance measures (route-based number of stops and delay) was analyzed in the cases where fixed-time control based on TOD plans was effective before the ATCSs deployment. It was found that delay and number of stops were reduced by 16.6 to 20.0%, as shown in Table 28. Compared with actuated (semi or fully) pre-ATCS signal control, these benefits are lower. These findings contradict a common perception that higher benefits are achieved when fixed-time TOD plans are replaced with an ATCS. However, it needs to be stated here that this comparison could be affected by some other factors, such as fine-tuning frequency, last time when signals were retimed, time span between before and after data collections performed for the evaluation study, etc.

Table 28 Performance improvements [%] for fixed-control pre-ATCS networks

Impact Type		Efficiency impact						Environmental impact				
Performance measure		Travel time		Delay		Number of stops	Queue length	Number of crashes	Fuel consumption	Emissions - HC	Emissions - CO	Emissions - NOx
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Routes based	Network level	Routes based	Routes based	Routes based	Routes based
AM peak hour	Average	-7.0	NR	-8.1	0.0	3.3	NR	NR	NR	NR	NR	NR
	STD	5.3	NR	0.2	NR	0.0	NR	NR	NR	NR	NR	NR
Mid-day peak hour	Average	-12.6	NR	-21.6	NR	-29.7	NR	-22.3	-2.8	-5.6	-2.2	-7.9
	STD	7.9	NR	8.3	NR	2.0	NR	0.0	0.0	0.0	0.0	0.0
PM peak hour	Average	-5.7	-10.8	-17.5	-19.6	-31.2	-9.7	NR	-6.5	-7.6	-7.4	-8.2
	STD	7.1	3.6	14.4	5.5	3.9	4.1	NR	0.0	0.0	0.0	0.0
Friday PM Peak Hour	Average	-11.2	-20.3	-10.9	-29.8	-22.5	-22.1	NR	-2.2	-1.1	0.5	-0.7
	STD	6.4	1.4	0.0	2.0	0.0	0.4	NR	0.0	0.0	0.0	0.0
Average Saturday	Average	-7.4	NR	-25.2	NR	-20.0	NR	NR	-3.3	-4.7	-2.8	-5.4
	STD	2.4	NR	8.1	NR	7.2	NR	NR	0.0	0.0	0.0	0.0
Average weekday	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
All periods	Average	-8.8	-15.5	-16.6	-16.5	-20.0	-15.9	-22.3	-3.7	-4.8	-3.0	-5.5
	STD	5.8	2.5	6.2	3.7	2.6	2.2	0.0	0.0	0.0	0.0	0.0

The next aspect of ATCS operations that can be investigated through the use of (AT)2C, is the impact of urban setting on the performance of the ATCS. To address this aspect, we examined operational improvements of the ATCSs for two area types - suburban and urban, shown in Tables 29 and 30, respectively. In the cases where ATCSs were deployed in suburban areas it is found, based on average values of all time periods, that improvements for all performance measures were achieved.

More specifically, for the set of efficiency-related performance measures benefits ranged from 8.8% to 20% for route-based travel time and number of stops, respectively. In terms of the environmental impacts, emission pollutants (HC, CO, NOx) were reduced anywhere from 3.0% to 5.5%. Fuel consumption and number of crashes were reduced by 3.7% and 22.3%, respectively.

Table 29 Performance improvements [%] for ATCSs in suburban areas

Impact Type		Efficiency impact							Environmental impact								
Performance measure		Travel time		Delay		Number of stops	Side street delay	Queue length	Number of crashes	Number of conflicts	Fuel consumption	Emissions - HC		Emissions - CO		Emissions - NOx	
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Routes based	Routes based	Network level	Network level	Routes based	Routes based	Network level	Routes based	Network level	Routes based	Network level
AM peak hour	Average	-7.8	-4.0	-29.4	-5.5	-23.3	NR	NR	NR	NR	-21.1	-28.9	-4.0	-13.3	-4.0	-13.2	-5.1
	STD	0.0	0.0	28.1	0.0	22.4	NR	NR	NR	NR	5.4	0.0	0.0	0.0	0.0	0.0	0.0
Mid-day peak hour	Average	-10.6	-8.0	-29.4	-5.8	-44.3	NR	NR	NR	NR	-45.4	-67.9	-9.9	-24.1	-5.9	-24.1	-9.3
	STD	11.2	0.0	60.2	0.0	29.1	NR	NR	NR	NR	17.3	0.0	0.0	0.0	0.0	0.0	0.0
PM peak hour	Average	-4.5	-6.1	-29.7	-11.2	-17.2	-45.1	-14.6	-20.8	-9.7	-9.6	-22.4	-10.0	-9.7	-5.4	-9.6	-21.1
	STD	12.4	18.3	19.1	28.8	19.4	0.0	7.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Friday PM Peak Hour	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	-10.4	NR	-35.1	NR	-11.1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	0.0	NR	0.0	NR	0.0	NR	NR	NR	NR	NR	NR	NR	0.0	NR	0.0	NR
Average weekday	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
All periods	Average	-8.3	-6.0	-30.9	-7.5	-24.0	-45.1	-14.6	-20.8	-9.7	-25.4	-39.7	-8.0	-15.7	-5.1	-15.6	-11.8
	STD	5.9	6.1	26.8	9.6	17.7	0.0	7.4	0.0	0.0	7.6	0.0	0.0	0.0	0.0	0.0	0.0

In the cases where ATCSs are deployed in more urban areas, we do not observe completely consistent trends in the reported performance measures. Table 30 shows that while the travel times, delays and stops (in average based on all of the time intervals) averaged for all time periods improve anywhere from 7.6% to 19.9%, side-street delays increase by 6%. However, as reported in one of the evaluation studies, side-street performance was improved by 11%, which was illustrated through the side street split failures. When impact on environment was examined, fuel consumption was decreased by up to 4%. Benefits for emission pollutants were mixed, varying between +1.3% and -5.4%. Average number of conflicts for all periods were decreased by 7.5%. When average number of crashes were analyzed decrease of 34.0% was reported.

Table 30 Performance improvements [%] for ATCSs in urban areas

Performance measure	Time Period		Travel time Routes based	Travel time Network level	Delay Routes based	Delay Network level	Split failure Network level	Number of stops Routes based	Number of stops Network level	Side street delay Routes based	Queue length Routes based	Side street split failure Network level	Transit travel time Network level	Number of crashes Network level	Number of conflicts Network level	Fuel consumption Routes based	Fuel consumption Network level	Emissions - HC Routes based	Emissions - HC Network level	Emissions - CO Routes based	Emissions - CO Network level	Emissions - NOx Routes based	Emissions - NOx Network level	Emissions - All pollutants Network level
AM peak hour	Average		-12.9	-15.3	-27.8	-15.6	NR	-27.8	-13.4	11.7	NR	NR	-3.8	NR	-5.9	-4.9	-1.5	-5.8	-0.4	-4.3	-0.4	-5.3	-2.4	-0.2
	STD		10.4	11.0	29.4	19.6	NR	46.5	10.6	20.8	NR	NR	0.0	NR	0.0	3.6	1.6	1.8	0.5	2.4	0.4	1.4	2.0	0.0
Mid-day peak hour	Average		-10.6	-16.7	-20.3	-21.4	NR	-21.0	-19.4	13.9	NR	NR	-4.6	-22.3	-8.4	-6.1	0.0	-12.9	0.1	-10.7	0.1	-12.1	0.0	-0.3
	STD		9.5	11.6	14.2	18.2	NR	15.6	20.4	19.5	NR	NR	0.0	0.0	0.0	6.7	0.0	8.4	0.0	9.0	0.0	8.1	0.0	0.0
PM peak hour	Average		-11.1	-5.0	-21.7	-9.9	NR	-22.0	-6.2	10.5	-9.2	NR	-2.6	-10.5	-8.1	-3.2	-1.0	-3.7	-1.2	-7.8	-1.2	-5.6	-1.1	NR
	STD		13.8	4.6	32.2	8.8	NR	30.3	11.8	22.4	3.8	NR	0.0	2.2	3.7	3.6	0.9	5.9	1.1	1.8	1.0	1.6	0.9	NR
Friday PM Peak Hour	Average		-13.0	-10.9	-12.6	-10.7	NR	-8.0	8.6	-3.5	-21.6	NR	NR	NR	NR	-2.2	3.5	-1.1	3.9	0.5	6.9	-0.7	1.9	NR
	STD		6.0	6.2	22.3	13.5	NR	41.1	14.7	0.0	0.0	NR	NR	NR	NR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NR
Average Saturday	Average		-10.2	NR	-29.9	-20.4	NR	-16.3	NR	NR	NR	NR	NR	NR	NR	-3.3	NR	-4.7	NR	-2.8	NR	-5.4	NR	NR
	STD		5.8	NR	15.0	0.0	NR	8.2	NR	NR	NR	NR	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR	NR
Average weekday	Average		-6.1	NR	-7.1	-1.0	-85.5	NR	NR	-1.6	NR	-11.0	-0.3	-69.0	NR	NR	-2.5	-4.5	NR	-3.0	NR	-2.5	NR	NR
	STD		2.4	NR	7.0	0.3	0.0	NR	NR	0.3	NR	0.0	0.0	0.0	NR	NR	0.5	4.5	NR	1.0	NR	1.5	NR	NR
All periods	Average		-10.6	-12.0	-19.9	-13.2	-85.5	-19.0	-7.6	6.2	-15.4	-11.0	-2.8	-34.0	-7.5	-4.0	-0.3	-5.4	0.6	-4.7	1.3	-5.3	-0.4	-0.3
	STD		8.0	8.4	20.0	10.0	0.0	28.3	3.2	12.6	1.9	0.0	0.0	0.7	1.2	2.8	0.6	3.4	0.4	2.4	0.4	2.1	0.7	0.0

Another type of analysis is to look into shape of the networks where the ATCSs have been deployed. From that perspective we recognized (for reasons to simplify possible records) ATCS which are deployed on single corridors, networks of two (dominant) intersecting corridors, and mixed networks (irregular networks with multiple dominant corridors). For each of these types of deploying ATCSs networks, performance improvements are presented in Tables 31, 32 and 33. For the most dominant network type (i.e. single corridor) covered by the evaluation studies, efficiency performance measures were improved anywhere from 2.8% (transit travel time) to 85.5% (split failure), over all of the observed periods. The only case when performance was worsened was for the side-street delay, which was increased by 6.3%. It needs to be mentioned that when a route performance is derived from the evaluation studies on a-single-corridor network, then such measures represent the main-street route. Generally, based on the results of the evaluated ATCS studies, one can conclude that the evaluated ATCSs did bring improvement in various environmental-impact related performance measures. Average fuel consumption (for all periods) was reduced in a range from 1.2% - 11.2% and emission pollutants were also decreased from 2.4% to 21.5%. Similarly, average number of crashes were reduced by 14%, whereas the average number of conflicts was reduced by 7.6%.

Table 31 Performance improvements [%] for ATCSs on single corridors

Performance measure	Time Period		Travel time Routes based	Travel time Network level	Delay Routes based	Delay Network level	Split failure Network level	Number of stops Routes based	Number of stops Network level	Side street delay Routes based	Queue length Routes based	Side street split failure Network level	Transit travel time Network level	Number of crashes Network level	Number of conflicts Network level	Fuel consumption Routes based	Fuel consumption Network level	Emissions - HC Routes based	Emissions - HC Network level	Emissions - CO Routes based	Emissions - CO Network level	Emissions - NOx Routes based	Emissions - NOx Network level
AM peak hour	Average		-10.7	-3.7	-31.8	2.7	NR	-33.7	-5.5	14.1	NR	NR	-3.8	NR	-5.9	-10.0	-1.5	-18.5	-1.6	-10.3	-1.6	-10.1	-3.3
	STD		0.0	4.1	30.7	0.0	NR	21.6	5.1	22.3	NR	NR	0.0	NR	0.0	8.7	1.6	8.5	1.5	2.5	1.5	2.5	2.1
Mid-day peak hour	Average		-11.1	-8.6	-39.0	0.1	NR	-34.4	-2.9	13.9	NR	NR	-4.6	NR	-8.4	-20.0	0.0	-47.3	-4.9	-24.8	-2.9	-24.6	-4.7
	STD		10.6	7.0	28.2	0.0	NR	27.1	2.4	19.5	NR	NR	0.0	NR	0.0	21.1	0.0	16.8	4.1	0.5	2.4	0.4	3.8
PM peak hour	Average		-10.7	-4.9	-24.1	-9.4	NR	-28.9	-11.3	0.8	-13.4	NR	-2.6	-14.0	-8.5	-3.5	-1.0	-15.8	-4.2	-10.1	-2.6	-7.4	-7.8
	STD		13.3	15.0	27.8	24.6	NR	24.3	7.9	32.0	6.6	NR	0.0	4.6	3.4	4.5	0.9	5.3	3.7	0.3	1.9	1.8	8.2
Friday PM Peak Hour	Average		-17.8	-3.3	-33.5	-3.9	NR	-57.4	-9.4	-3.5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD		1.0	0.0	1.5	0.0	NR	0.0	0.0	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average		-11.7	NR	-34.7	NR	NR	-10.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD		5.6	NR	14.5	NR	NR	3.5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average		-6.1	NR	-14.0	NR	-85.5	NR	NR	NR	NR	-11.0	-0.3	NR	NR	NR	-2.5	-4.5	NR	-3.0	NR	-2.5	NR
	STD		2.0	NR	0.8	NR	0.0	NR	NR	NR	NR	0.0	0.0	NR	NR	NR	0.4	3.7	NR	0.8	NR	1.2	NR
All periods	Average		-11.3	-5.1	-29.5	-2.6	-85.5	-32.9	-7.3	6.3	-13.4	-11.0	-2.8	-14.0	-7.6	-11.2	-1.2	-21.5	-3.6	-12.0	-2.4	-11.1	-5.2
	STD		5.4	6.5	17.3	6.1	0.0	15.3	2.7	18.5	6.6	0.0	0.0	4.6	1.1	11.4	0.7	8.6	3.1	1.0	2.0	1.5	4.7

In the case when two intersecting corridors are evaluated, as shown in Table 32, results of evaluation are strongly dependent on the time of day when evaluation is conduced. It can be observed that during somewhat lighter traffic conditions (i.e., mid-day peak hour) higher benefits were reported (for almost all performance measures) than those relevant for morning and evening peak traffic conditions. All of the performance measures were improved by 3.4-14.3%, except the route-based delay, which was increased significantly. It needs to be highlighted that this result was highly impacted by a single evaluation study (essentially an outlier) where route-based delay was increased by 112%.

Table 32 Performance reduction [%] for ATCSs on two intersecting corridors

Impact Type		Efficiency impact						Environmental impact			
Performance measure		Travel time		Delay		Number of stops		Fuel consumption	Emissions - HC	Emissions - CO	Emissions - NOx
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Routes based	Routes based	Routes based
AM peak hour	Average	0.6	-4.0	-23.5	NR	36.4	NR	-6.7	-3.5	-1.3	-3.5
	STD	23.2	0.0	6.3	NR	57.0	NR	0.0	0.0	0.0	0.0
Mid-day peak hour	Average	-11.3	-8.0	52.3	NR	-14.3	NR	-4.8	-6.5	-4.5	-3.4
	STD	6.4	0.0	49.0	NR	2.9	NR	0.0	0.0	0.0	0.0
PM peak hour	Average	9.0	-4.0	-27.6	0.1	20.3	14.3	-4.8	5.9	-5.5	-3.6
	STD	15.7	0.0	37.4	0.0	24.5	0.0	0.0	0.0	0.0	0.0
Friday PM Peak Hour	Average	NR	NR	27.4	4.1	56.0	26.6	NR	NR	NR	NR
	STD	NR	NR	0.0	0.0	0.0	0.0	NR	NR	NR	NR
Average Saturday	Average	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Average weekday	Average	NR	NR	NR	-0.6	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	0.0	NR	NR	NR	NR	NR	NR
All periods	Average	-0.6	-5.3	7.1	1.2	24.6	20.5	-5.4	-1.4	-3.8	-3.5
	STD	15.1	0.0	23.2	0.0	21.1	0.0	0.0	0.0	0.0	0.0

For mixed networks (usually combining several intersecting corridors) Table 33 shows reductions of all efficiency-based performance measures (averaged for all periods) in a range between 5.1% to 28.5%. Increase in emissions was also noted during special events.

Table 33 Performance improvements [%] for ATCSs in mixed networks

Impact Type		Efficiency impact								Environmental impact									
Performance measure		Travel time		Delay		Number of stops		Side street delay	Queue length	Number of crashes	Fuel consumption		Emissions - HC		Emissions - CO		Emissions - NOx		Emissions - All polutants
Time Period		Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Routes based	Network level	Network level
AM peak hour	Average	-17.4	-27.0	-1.0	-17.7	-31.7	-29.1	2.3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	-0.2
	STD	5.3	2.6	6.0	18.3	28.6	0.0	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.0
Mid-day peak hour	Average	-9.1	-32.8	-21.6	-23.3	-35.0	-52.6	NR	NR	-22.3	-2.8	NR	-5.6	NR	-2.2	NR	-7.9	NR	-0.3
	STD	8.9	0.0	8.3	16.5	6.7	0.0	NR	NR	0.0	0.0	NR	0.0	NR	0.0	NR	0.0	NR	0.0
PM peak hour	Average	-10.3	-8.9	-26.4	-14.1	-33.4	NR	-16.0	-3.8	NR	-6.5	NR	-7.6	NR	-7.4	NR	-8.2	NR	NR
	STD	3.2	0.0	6.7	8.1	4.3	NR	0.0	0.0	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR	NR
Friday PM Peak Hour	Average	-3.3	-18.5	-10.9	-32.2	-22.5	NR	NR	-21.6	NR	-2.2	3.5	-1.1	3.9	0.5	6.9	-0.7	1.9	NR
	STD	0.0	0.0	0.0	0.0	0.0	NR	NR	0.0	NR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NR
Average Saturday	Average	-7.4	NR	-25.2	-20.4	-20.0	NR	NR	NR	NR	-3.3	NR	-4.7	NR	-2.8	NR	-5.4	NR	NR
	STD	2.4	NR	8.1	0.0	0.0	NR	NR	NR	NR	0.0	NR	0.0	NR	0.0	NR	0.0	NR	NR
Average weekday	Average	NR	NR	-0.2	-1.2	NR	NR	-1.6	NR	-69.0	NR	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	0.7	0.0	NR	NR	0.3	NR	0.0	NR	NR	NR	NR	NR	NR	NR	NR	NR
All periods	Average	-9.5	-21.8	-14.2	-18.1	-28.5	-40.9	-5.1	-12.7	-45.7	-3.7	3.5	-4.8	3.9	-3.0	6.9	-5.5	1.9	-0.3
	STD	4.0	0.6	4.9	7.1	9.4	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Finally, we look at the ATCS performance from another perspective – based on how was an ATCS selected during the procurement process. Two major ways to select an ATCS are competitive bidding versus a sole-source procurement. Each method does not have much with ATCS performance but a point could be made, for either approach, that the selection process may result in a better/worse performing system (e.g. sometimes a good but more expensive system could be missed through the competitive bidding process). Tables 34 and 35 show performance improvements for sole-source and competitive bidding approaches, respectively.

Table 34 Performance improvements [%] of the sole-source selected ATCSs

Impact Type		Efficiency impact				Environmental impact			
Performance measure		Travel time	Delay		Number of stops	Fuel consumption	Emissions - HC	Emissions - CO	Emissions - NOx
Time Period		Routes based	Routes based	Network level	Routes based	Network level	Routes based	Routes based	Routes based
AM peak hour	Average	-10.6	-28.8	-5.5	-32.1	NR	NR	NR	NR
	STD	0.0	37.4	0.0	24.7	NR	NR	NR	NR
Mid-day peak hour	Average	-11.3	-1.4	-5.8	-34.1	NR	NR	NR	NR
	STD	9.9	0.0	0.0	23.0	NR	NR	NR	NR
PM peak hour	Average	-14.2	-48.4	-10.7	-37.2	NR	NR	NR	NR
	STD	12.8	25.1	6.7	26.0	NR	NR	NR	NR
Friday PM Peak Hour	Average	NR	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	-11.0	-37.0	NR	NR	NR	NR	NR	NR
	STD	0.0	0.0	NR	NR	NR	NR	NR	NR
Average weekday	Average	-9.0	-13.0	NR	NR	-3.0	-9.0	-4.0	-4.0
	STD	0.0	0.0	NR	NR	0.0	0.0	0.0	0.0
All periods	Average	-11.2	-25.7	-7.3	-34.5	-3.0	-9.0	-4.0	-4.0
	STD	4.5	12.5	2.2	24.6	0.0	0.0	0.0	0.0

When analyzing performance measures for these two selection methods, one can observe that the results for delays of the ATCSs acquired through the competitive bidding process outperform those of the sole-source method. However, when we observe travel time and number of stops the opposite findings can be observed. These results are not surprising – a number of cases where sole-source method has been deployed could be attached for call to address objective functions offered by those ATCS brands which may improve more significantly progression of major traffic movements while maybe neglecting overall network performance.

Table 35 Performance reduction [%] for ATCSs for ATCSs competitive bidding selection

Impact Type		Efficiency impact			Environmental impact			
Performance measure		Travel time	Delay	Number of stops	Fuel consumption	Emissions - HC	Emissions - CO	Emissions - NOx
Time Period		Routes based	Routes based	Routes based	Routes based	Routes based	Routes based	Routes based
AM peak hour	Average	-8.64	-26.87	-15.32	-6.67	-3.54	-1.34	-3.52
	STD	11.52	19.73	9.95	0.00	0.00	0.00	0.00
Mid-day peak hour	Average	-7.49	-29.96	-20.01	-4.83	-6.45	-4.47	-3.38
	STD	5.96	15.19	7.94	0.00	0.00	0.00	0.00
PM peak hour	Average	-6.61	-27.83	-20.42	-4.78	5.93	-5.46	-3.62
	STD	9.01	9.35	12.51	0.00	0.00	0.00	0.00
Friday PM Peak Hour	Average	NR	NR	NR	NR	NR	NR	NR
	STD	NR	NR	NR	NR	NR	NR	NR
Average Saturday	Average	-6.15	-24.14	-8.44	NR	NR	NR	NR
	STD	3.43	8.93	2.18	NR	NR	NR	NR
Average weekday	Average	-3.21	NR	NR	NR	NR	NR	NR
	STD	0.00	NR	NR	NR	NR	NR	NR
All periods	Average	-6.42	-27.20	-16.05	-5.43	-1.35	-3.76	-3.51
	STD	5.98	13.30	8.14	0.00	0.00	0.00	0.00

CHAPTER 7 CONCLUSIONS AND SUGGESTED RESEARCH

This study attempts to provide a comprehensive analysis of the ATCSs deployed and evaluated in the US. Based on multiple data collection methods (e.g. literature review, survey of deploying ATCS agencies), the data collected on the number of ATCSs were sorted according to the framework developed for ATCS data categorization. Collected data were used to populate the database developed as an MS Excel spreadsheet which was connected to its 'front-end' – a user friendly interface developed with a purpose to provide an intuitive tool for users to retrieve relevant information. Such an integrated database, with its back-end (data table) and front-end interface (i.e. dashboards) represent the (AT)2C. The (AT)2C can be utilized to select a number of data based on queries/filters develop in friendly way for an easy information retrieval.

The survey developed for ATCS-deploying agencies was delivered to 349 agencies in the US and 11 in Canada. A total of 35 agencies responded to the survey, out of which 6 did not have any ATCS results to report. Consequently, these six agencies were excluded from the study. On the other hand, the authors identified additional 25 ATCS-deploying agencies from a broad literature review. In total data for 54 agencies which deployed one or more ATCSs were collected, out of which 24 were cities, 10 counties, and 20 states.

In total, it was reported 140 ATCS deployments, out of which details were provided for 81 deployments. For the reported deployments 70 evaluation studies were conducted. However, of those 70 evaluation studies results were provided for 59 studies. It needs to be mentioned that 10 ATCSs were evaluated multiple times resulting with 14 additional studies. Interestingly, the literature review has shown that some agencies decide to evaluate ATCSs in simulation environment prior to making decision about deployment. These 12 evaluations were also reviewed and used to populate the database. In total 85 evaluation studies were populated in the database of the (AT)2C.

The findings about urban environment of the ATCSs show that 44% of the deployed ATCSs were within urban areas, 22% in suburbs, 1% in CBD and for the remaining 14% the area type was not specified. In 51% of the cases, the ATCSs were deployed on single corridor networks, whereas 15% of the deployments were on two intersecting corridors and mixed networks. When the deployments were stratified by amount of vehicular traffic on the major corridors the findings show that around 31% of deployed systems work with AADT ranges 35,000-45,000, 22% work with AADTs between 25,000 - 35,000, 18% of ATCSs accommodate AADTs less than 25,000, and 26% of deployments work with AADTs higher than 45,000.

Based on the 36 deployed ATCSs, from which 58% are deployed in the period between 2015 and 2019, it is shown that 64% of deployed ATCSs are integrated (to some extent) with high-resolution data analyzing and reporting capabilities. In addition, 15% of deployed systems have some integration with vehicle to infrastructure technologies.

Reported average costs of ATCS installations are around $55,000 per intersection. Average costs of ATCS software licensing are around $10,000 (per intersection) and finally the average ATCS maintenance costs, per intersection per year, are approximately $4,000. In 36% of the deployments, system engineering analysis was conducted prior to an ATCS installation. Evaluation of an ATCS was initiated in 48% by deploying ATCS agency. In 45% of the cases, the same entity that initiated evaluation study, later, conducted data collection and reported results.

Based on 85 evaluation studies entered in the database, average benefits of ATCSs can be estimated (for efficiency-based performance measures) in a range from 7.8% (number of stops) to 85% (split failure), when all evaluation periods are combined (regular (i.e., typical weekday, Mon-Thu), oversaturated traffic conditions (e.g., Friday PM peak hour) and weekend traffic). Although the range of improvements is not stellar, the results are quite consistent and they also report an increase in side-street delays for 3.4%. Similarly, transit travel times were reduced, overall, by 2.8% on average for all of the investigated periods. In terms of environmental impacts, an average fuel reduction ranged from 0.3% to 7%, whereas emission

pollutants were also decreased from 0.1% to 9.8%. Finally, it was found that a number of crashes was decreased by 35.1% while an average number of conflicts was reduced by 7.6%.

When each ATCS brand was examined individually to understand benefits in achieved performance, overall findings (averaged over all time periods) show that benefits were achieved in most of the cases. However, in some instances ATCSs failed to outperform previous type of control. Since each evaluation represents a specific case, readers are encouraged to investigate specific cases of their interests by using the (AT)2C and relevant referenced studies.

Investigation of various AADT levels, as a proxy of overall traffic congestion, has shown that higher benefits were achieved on networks with moderate traffic (i.e., AADT is between 35,000 and 55,000) than on those with high traffic (AADT higher than 55,000). This is the case for all of the efficiency-based performance measures. However, when ATCSs deployed on the roads with relatively low AADTs (i.e., less than 35,000) are compared with those from any other AADT group (i.e., moderate, high), the results are not consistent. In terms of impact of signal retiming frequency of the pre-ATCS signals, it was found that higher benefits (for all periods considered) were achieved for moderately frequently retimed signals than for very frequently retimed signals. When results from relatively rarely retimed signals were compared with other retiming frequencies, results were not consistent to draw a meaningful conclusion.

When different pre-ATCS signal control types were analyzed, it was found that benefits from evaluated ATCSs tends to be higher when ATCSs are installed on networks previously controlled by semi-actuated signals than if fully-actuated signals were present. When benefits of ATCS deployments were correlated to the urbanization of the network, the observed results were consistent. ATCSs deployed in suburban environments reported improvement in all efficiency-related performance measures. Similarly, the same trend was observed for systems deployed in urban areas with one exception, side-street delay was increased by 6.2% (for all periods averaged).

For the most dominant network type, which is a single corridor, covered by the evaluation studies, efficiency performance measures were improved anywhere between 2.8% (transit travel time) and 85.5% (split failure), averaged over all time periods. Only delay side-streets was worsened by 6.3%. In cases when ATCSs were deployed on two intersecting corridors, for all combined periods, it was found that delay and number of stops were increased by 7.1% and 24.6%, respectively, although, other performance measures were improved (e.g. network-based travel time by 5.4%). In the case of mixed networks over all combined periods, findings show that ATCSs were capable of improving all efficiency-based performance measures between 5.1% (side street delay) and 40.9% (network-based number of stops). However, these results were not consistent in terms of environmental-impact performances.

When compared to some of the previous studies, where focus was given to overall experiences of the ATCS agencies, this study allows researchers to step into details (as recorded in the database) of each ATCS deployment/evaluation and investigate numerous criteria. On the other hand, considering that such a large number of criteria required a time-consuming data entry process for agencies' representatives, a relatively low survey response rate was achieved. In addition, not all of the data categories (answers) were reported for all of the ATCS deployments. Some of the reasons for this omission could be the length of survey, lack of the knowledge to provide relevant answers, lack of the relevant data, etc.

Limitations of this study are mainly related to the data collection methods. In the first place, a small response rate from agency representative's prevented collection of a large data sample to develop a robust database. In some cases, agency's staff (who possess proper knowledge) was not available during the survey's open window, which impacted the quality of the feedback received. On the other hand, when the relevant data are collected only through the literature review, it was impossible to get all of the required information from the available data.

Future research should be directed in periodical maintenance of the database by entering new data entries. Findings show that several ATCS deployments within the last five years integrated some elements of the emerging technologies. It is expected that this trend will continue in the following years; thus, it is of particular importance to monitor how these applications will be affecting ATCSs and their management and operations.

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G L O S A R Y

ACDSS – Adaptive Control Decision Support System

ACS Lite – Adaptive Control Software Lite

ATCS – Adaptive Traffic Control System

(AT)2C – Assessment Tool for Adaptive Traffic Control

AASHTO American Association of State Highway and Transportation Officials

AADT – Average Annual Daily Traffic

CO – Carbon Monoxide

CORSIM – CORridor SIMulation

DOT – Department Of Transportation

D4 – Fourth Dimension Traffic

FHWA – Federal Highway Administration

HC – Hydrocarbons

ITS – Intelligent Transportation Systems

NCHRP – National Cooperative Highway Research Program

NOx – Nitrogen Oxides

OPAC – Optimization Policies for Adaptive Control

P2P – Peer to Peer

RHODES – Real-Time Hierarchical Optimized Distributed and Effective System

SCATS – Sidney Coordinated Adaptive Traffic System

SCOOT – Split Cycle Offset Optimization Technique

SE – System Engineering

SUTRAC – Scalable Urban Traffic Control

TOD – Time Of Day

UTOPIA – Urban Traffic Optimization by Integrated Automation

V2I – Vehicle-to-Infrastructure

APPENDIX A   LIST OF EVALUATION STUDIES

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APPENDIX B   FRAMEWORK FOR DATA CATEGORIZATION

1. Introduction

The purpose of this document is to present identified categories to classify/filter various data from ATCS evaluation studies. In order to provide consistent way for data categorization of ATCS evaluations, framework has been developed. A need for such a framework lies in fact that each ATCS deployment is somewhat unique.

For example, a particular ATC system 'X' was deployed by an agency 'A' on a suburban arterial with 7 signals where previous type of signal control was non-coordinated, fixed-time signals where an evaluation study was performed in the 'before-after' fashion by using floating car data and comparing travel times as the only way of measuring the system performance. In another case, an ATC system 'Y' was deployed by an agency 'B' in the CBD area on a grid network, operating 25 signals where previous type of control was fully-actuated coordinated signals, and where evaluation was conducted by using a simulation tool VISSIM with multiple performance measures available. From these two illustrative examples one can see how two ATC deployments and evaluations could be quite different and difficult to compare to each other to withdraw some aggregated lessons learned. Thus, it is important to identify all relevant categories which define an ATCS deployment and its evaluation so that interested parties (e.g. (AT)2C users) have a consistent way to filter out specific information from a database of ATCS deployments/evaluation studies.

Thus, the goal is to develop such a framework which will help users to filter out relevant ATCS deployment/evaluation cases. For this reason, the framework significantly relies on the proper definition of relevant fields, categories and sub-categories that can be used to retrieve appropriate case studies and data from a database that represents a library of the existing evaluation studies. The FAU research team's objective under this task is to identify such categories and present them in a coherent and consistent way so that most querying and filtering on ATCS evaluation studies can be done in a proper manner.

In order to develop categories for ATCS evaluation, the FAU research team conducted traditional literature review where studies were retrieved from relevant databases by using a number of keywords such as *ATCS, ATCS evaluations, ATCS deployments, etc.* Gathered studies were then reviewed in order to establish categories for ATCS evaluations. It needs to be stated that the categories presented in this framework represent the final list of categories included in the (AT)2C.

2. Framework for Data Categorization of ATCS Evaluations

Framework for Data Categorization of ATCS evaluations consists of four identified areas (annotated as Sections, see Figure 1), where within each area categories and sub-categories are listed and described.
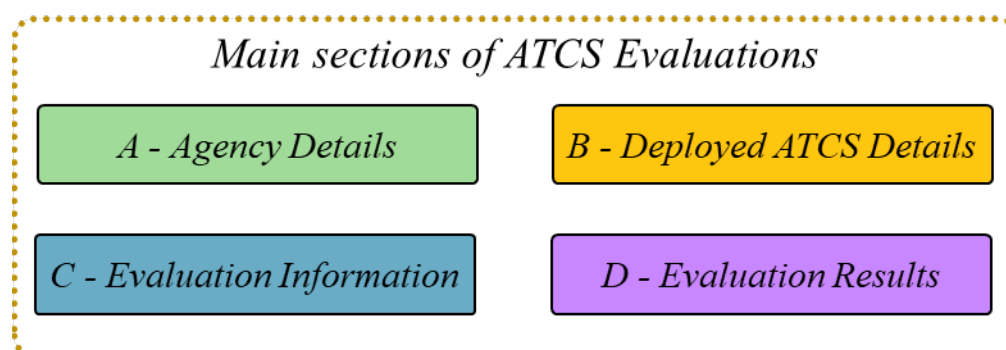
Figure 49 Main sections regarding ATCS Evaluations

2.1 Section A) Agency Details

All information about a particular agency, which deployed an ATCS, are gathered within section agency details. The FAU research team identified four (4) categories which include all important aspects of an agency that may influence deployment and operations of an ATCS. These categories are related to agency jurisdiction, organizational context of the agency (management), and budgeting. Within these categories following sub-categories were identified as shown in Figure 2.
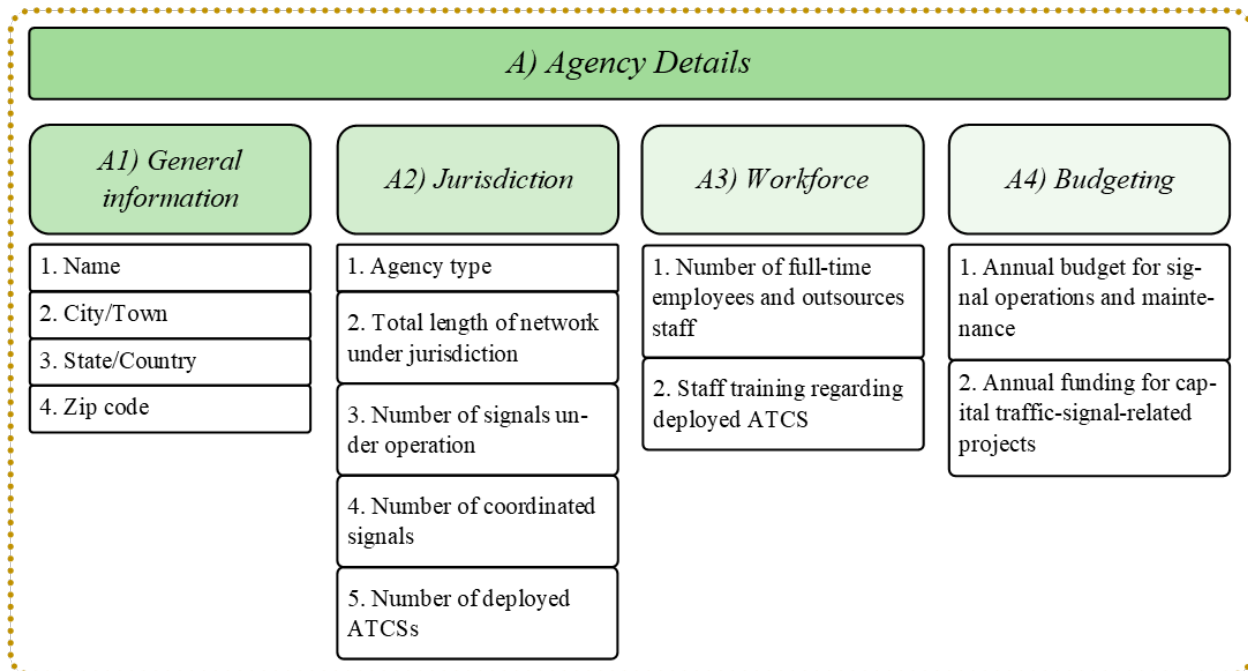
Figure 50 Categories and sub-categories within section A

Following represent the most relevant questions that are addressed within this framework:
1. What is covered within each category/sub-category?
2. Why particular category should be included in the framework?
3. How will the data for such category be obtained?
4. How will the collected data in the proposed framework be utilized?

Table 1 provides answers to these questions. For the question 1, the FAU research team provides brief definition of each category/sub-category. To address the question 2, the FAU research team emphasizes the importance of particular sub/category in decision-making process. For the question 3, it is explained if the relevant data can be collected through survey and/or from other relevant evaluation studies.

Before going to the question 4, it needs to be stated that outcomes of this project are twofold: (i) development of database-driven intuitive tool for data filtering and information retrieval and (ii) final report, which will document all of the research efforts including the objectives, research approach, findings, conclusions, and recommendations for future research. Thus, most of the collected data will be utilized for one of these two purposes – e.g. for the purpose of filtering or reporting or both purposes (filtering and reporting).

The FAU research team expects that user of the database-driven tool (i.e., Assessment Tool for Adaptive Traffic Control (AT2C)), will base his/her analysis (filtering process) on intuitive sub-categories such as, A2)1 Total length of road network under management, A2)4 Number of deployed ATCS systems etc. However, there are some less-intuitive sub-categories (e.g., A3)2 Staff training regarding deployed ATCS, B3)2 Who was involved in process of decision making?) that may be more useful for reporting purposes than for the filtering itself.

For example, sub-category A3)2 Staff training regarding deployed ATCS, represents one of the sub-categories which are used to describe an amount of training an agency staff received to operate and maintain their adaptive system.

Table 1 Definitions, justifications, process of gathering and usage of data within Section A

<table>
<tr><th colspan="8" align="center">SECTION A</th></tr>
<tr>
<th>Section</th>
<th>Category</th>
<th>Category explanation</th>
<th>Sub-category</th>
<th>Definition of sub-category</th>
<th>Justification</th>
<th>Obtained from</th>
<th>Used for</th>
</tr>
<tr>
<td rowspan="9">A) Agency Details</td>
<td rowspan="4">A1) General information</td>
<td rowspan="4">This category is developed in order to identify and distinguish agencies which deploy an ATCS</td>
<td>1. Name</td>
<td>1. Name of the agency under which management is deployed ATCS system</td>
<td>1. As a carrier of information under which agency jurisdiction ATCS is deployed, this sub-category is useful to identify all deployments/evaluations conducted under particular agency.</td>
<td>Evaluation study / Survey</td>
<td>Report</td>
</tr>
<tr>
<td>2. City/Town</td>
<td>2. City/Town in which agency is located</td>
<td rowspan="3">2-4. Supplemental information about agency which are going to be used for report.</td>
<td rowspan="3">Evaluation study / Survey</td>
<td rowspan="3">Report</td>
</tr>
<tr>
<td>3. State/County</td>
<td>3. State/Country in which agency is located</td>
</tr>
<tr>
<td>4. Zip Code</td>
<td>4. Zip code of the address where agency is located</td>
</tr>
<tr>
<td rowspan="5">A2) Jurisdiction</td>
<td rowspan="5">Agency jurisdiction in this context relates to the most important attributes which provide an insights of agency capability to monitor and operate traffic signals</td>
<td>1. Total length of road network under management</td>
<td>1. Total length of the road network under jurisdiction (not including private roads)</td>
<td rowspan="2">1-2. These two sub-categories provide an insight on capability of the agency to manage particular length of the network with a particular number of traffic signals. This helps (AT)2C users to filter out only those evaluations where network size and number of signals are within his/her area of interest</td>
<td>Survey</td>
<td>Filtering + Report</td>
</tr>
<tr>
<td>2. Number of signalized intersections</td>
<td>2. Number of signalized intersections under jurisdiction</td>
<td>Survey</td>
<td>Filtering + Report</td>
</tr>
<tr>
<td>3. Number of coordinated corridors</td>
<td>3. Number of coordinated signals under jurisdiction</td>
<td rowspan="2">3-4. In addition to the previous two sub-categories, these two allow more in-depth filtering options regarding agency capabilities.</td>
<td>Survey</td>
<td>Filtering + Report</td>
</tr>
<tr>
<td>4. Number of deployed ATCS systems</td>
<td>4. Number of deployed ATCS systems under jurisdiction</td>
<td>Survey</td>
<td>Filtering + Report</td>
</tr>
<tr>
<td>5. Name(s) of deployed ATCS system(s)</td>
<td>5. Name(s) of the deploying ATCS brand(s)</td>
<td>5. Each adaptive system on market has its own characteristics so it is important to enable filtering option in (AT)2C according to the type of system (InSync, SCOOT, etc.).</td>
<td>Evaluation study / Survey</td>
<td>Filtering + Report</td>
</tr>
</table>

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
A) Agency Details	A3) Management	Agency management in this context refer to a number of employees (per structure) and their training regarding signal operations	1. Number of full-time employees and outsourced staff	1. Total number of full-time employees (40-hours) and outsourced staff per different position	1. A number of employees and outsourced staff can illustrate agency readiness to operate ATCSs. It is important to identify this category in order to understand best practice of deploying ATCSs agencies.	Survey	Report
			2. Staff training regarding deployed ATCS	2. Total number of training hours per training type (Basic signal timing, advanced signal timing, ITS courses, hardware and communications and other). The number should be a product of number of staff and the training hours each member had per type of training	2. Similar to justification 1. above - it is important to identify the amount of received training regarding deployed ATCSs for deploying agencies.	Survey	Report
	A4) Budgeting	From perspective of agency budgeting for this study only annual maintenance costs will be examined	1. Estimated annual budget for signal operations and maintenance	1. Approved funding for traffic signal operations and maintenance	1-2. It is likely that agencies, which have a large budget for signal operations and maintenance, achieve higher benefits from an ATCS deployment. The future user of (AT)2C might want to perform filtering just for a certain amount of funding for maintenance (which can match with the amount in the subject agency).	Survey	Filtering + Report
			2. Estimated annual budget for capital traffic-signal-related projects	2. Approved funding for traffic capital traffic-signal-related projects			

2.2 Section B) Deployed ATCS

In this section we examine data categories related to deployed ATCSs. So far, the FAU Research team identified 6 categories which examine deployment of ATCS from perspective of:

1. Selection method and installation of ATCS
2. About area where ATCS is deployed
3. Area coverage of the ATCS
4. Objectives and operational environment
5. Communications and detection of ATCS
6. Previous traffic control system
7. Capital and maintenance costs
8. System monitoring and operating

For each identified category, the FAU research team developed sub-categories in order to identify important factors regarding particular ATCS deployment. Identified data categories and sub-categories are provided in Figure 3. In table 2, the FAU research team listed definitions, justifications, and explanations how the data will be collected and used.

B) Details of Deployed ATCSs

B1) Selection method and Installation of ATCS	B2) About area where ATCS is deployed	B3) Area coverage of the ATCS	B4) Objectives and operational environment	B5) Communications and detection of the ATCS	B6) Previous traffic control system	B7) Capital and maintenance costs	B8) System monitoring and operating
1. ATCS selection method	1. City	1. Network type	1. Main reason(s) for ATCS implementation	1. Transmission media	1. Previous type of traffic signal operations	1. Average costs of installation per intersection	1. How understandable are working principles of deployed ATCS?
2. Installation timeline	2. Zip code	2. Urban area type	2. ATCS performance assessment	2. Detection layout	2. Previous control type on ATCS deployed corridor/ network	2. Costs of installation of ATCS software	2. Which signal timing parameters can be adjusted in real time?
3. Installation issues	3. City population	3. Length of covered network	3. ATCS multimodal environment	3. Detection technology	3. When was the last time when signals were retimed on the subject network?	3. Average maintenance costs of ATCS per year	3. Expected ATCS life cycle
4. Status of deployed ATCS	4. Metropolitan Area	4. Number of signals	4. ATCS integration with emerging technologies		4. Previous signals fine-tuning frequency		
5. Who was involved in process of decision making?	5. Metropolitan area population	5. AADT					

Figure 51 Categories and sub-categories within section B

Table 2 Definitions, justifications, process of gathering and usage of data within Section B

<table>
<tr><th colspan="8">SECTION B</th></tr>
<tr><th>Section</th><th>Category</th><th>Category explanation</th><th>Sub-category</th><th>Definition of sub-category</th><th>Justification</th><th>Obtained from</th><th>Used for</th></tr>
<tr>
<td rowspan="5">B) Deployed ATCS</td>
<td rowspan="5">B1) Selection method and installation of ATCS</td>
<td rowspan="5">Details regarding ATCS selection procedures and installation Details regarding ATCS selection procedures and installation</td>
<td>1. ATCS selection method</td>
<td>1. ATCS selection method shows how particular deployed ATSC was selected</td>
<td>1. In most of the cases, selection of ATCS can be performed by examining several ATCS brands or single. Form that perspectives, selection method is competitive bidding or sole source. This category is established in order to investigate are there particular relationships between selection methods and obtained benefits of deployed ATCS.</td>
<td>Survey</td>
<td>Filtering + Report</td>
</tr>
<tr>
<td>2. Installation timeline</td>
<td>2. Installation timeline contain information when for deployed ATCS installation started and finished</td>
<td>2. This category is introduced to relate temporal component for each ATCS deployment. Moreover, it can be used to perform specific analysis for different times.</td>
<td>Evaluation study / Survey</td>
<td>Filtering + Report</td>
</tr>
<tr>
<td>3. Installation issues</td>
<td>3. Installation issues are related to all unplanned anticipated activities during an ATCS installation</td>
<td>3. Installation issues are defined in order to investigate what are the main reasons that agency face while installing an ATCS.</td>
<td>Evaluation study / Survey</td>
<td>Report</td>
</tr>
<tr>
<td>4. Status of deployed ATCS</td>
<td>4. Status of deployed ATCS can be, operational (partially or fully) or decommissioned (partially or fully)</td>
<td>4. From the time when a system was deployed until surveying date it is important to investigate are these systems are operational or not. If not, main reasons for system decommissioning are covered.</td>
<td>Evaluation study / Survey</td>
<td>Report</td>
</tr>
<tr>
<td>5. Who was involved in process of decision-making?</td>
<td>5. Process of decision making towards implementation of an ATCS should include various stakeholders such as, sponsoring agency, transit agencies, railroad operators etc. Here, we want to identify who was included in this process.</td>
<td>5. Stakeholder coordination represents a good technique in any program development process. As a successful deployment of an ATCS requires both, knowledge and involvement of decision-makers, within this category we investigate the most common stakeholders involved in the process of ATCS decision making.</td>
<td>Evaluation study / Survey</td>
<td>Report</td>
</tr>
</table>

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
B) Deployed ATCS	B2) About area where ATCS is deployed	General information regarding area where an ATCS is deployed General information regarding area where an ATCS is deployed	1. City	1. City where ATCS system is deployed	1. This category is developed in order to filter out all of the ATCS deployments within the particular city. A user of future (AT)2C may want to know about all ATCS deployments and evaluations in a particular city.	Evaluation study / Survey	Filtering + Report
			2. Zip code	2. Zip code of the city where ATCS is deployed	2. Supplemental information about the city where an ATCS is deployed.	Evaluation study / Survey	Report
			3. City population	3. Population size for the city where ATCS is deployed	3. Population size of a city is usually correlated with traffic patterns, such as demand, time and spatial distribution of flows etc. For cities with higher population one can expect higher traffic demands and a higher impact on transportation network during rush hours. User of future (AT)2C may find this sub-category relatively intuitive in the filtering process when trying to find evaluations for all of the cities with a certain population range.	Evaluation study / Survey	Filtering
			4.1. Is City part of Metropolitan Area (MA)	4.1. This question applies only if a city is part of metropolitan area	4.1 Some ATCS deployments are within cities which are not parts of a metropolitan area and opposite. This is important to distinguish since cities outside of MA may have distinctive jurisdictional, economical and commuting patterns (e.g., more days in a year with irregularities in traffic flow).	Evaluation study / Survey	Filtering
			4.2. Metropolitan Area	4.2. Name of corresponding metropolitan area	4.2 User of future (AT)2C can filter deployments/evaluations for a specific metropolitan area.	Evaluation study / Survey	Filtering
			5. MA population	5. Population size of the metropolitan area	5. Supplemental information about the city where ATCS is deployed.	Evaluation study / Survey	Filtering

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
B) Deployed ATCS	B3) About coverage of the ATCS	General information regarding network where an ATCS is deployed	1. Network type	1. Network type in this context represent topology of network for which an ATCS is deployed, such as, grid, ring, single corridor, two intersecting corridors and irregular.	1. Each network type has its own characteristics and logic in traffic operations and management, so the results of an ATCS evaluation cannot be put under the same category. For example, in case that user of future (AT)2C wants to examine deployments of ATCS for single arterial corridors he/she will find other types of network irrelevant for his/her goal.	Evaluation study / Survey	Filtering + Report
			2. Urban area type	2. Here, we define area type, such as, CBD, urban or suburban areas.	2. Area type, such as CBD, urban or suburban areas, have distinctive traffic demand, conditions, and patterns. Comparison of one ATCS evaluation from CBD and a suburban arterial road is not consistent due to each of the characteristics of the area. Moreover, the user of future (AT)2C tool might be interested just to perform filtering for only one specific area type (e.g., CBD) finding other irrelevant.	Evaluation study / Survey	Filtering + Report
			3. Length of covered network	3. Total mileage of network covered under each ATCS deployment. For single corridor it represents length from center to center of first and last intersection, for more complex networks, such as grid, sum of distances between adjacent signalized intersections (which are part of ATCS) is used to determine total length of covered network	3. In early developments of some ATCS systems, this was an indicative parameter of system operative capability. Since some of ATCSs are present in the market for the relatively long period and some are in the relatively early stage of development we found this sub-category of particular importance. In cases where an agency is interested in an ATCS deployment and wants to find out benefits of certain ATCS evaluation for particular corridor length (e.g. 7 miles), a user of future (AT)2C may find other deployments irrelevant.	Evaluation study / Survey	Filtering + Report
			4. Number of signals	4. Total number of signalized intersections under ATCS jurisdiction	4. In addition to justification 3, a number of signals represent another indicative parameter for an ATCS capability. In the same manner, if an agency interested in ATCS deployment wants to find out benefits in (AT)2C for a particular number of signals (e.g., 13), finding other (e.g., 30) irrelevant.	Evaluation study / Survey	Filtering + Report

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
B) Deployed ATCS	B3) About network where ATCS is deployed	General information regarding network where an ATCS is deployed	5. AADT	5. AADT on the busiest road where particular ATCS is deployed	5. In addition to justification 3 and 4, AADT on the busiest road where particular ATCS is deployed represent another indicative parameter for an ATCS capability. In the same manner, if an agency interested in ATCS deployment wants to find out benefits in (AT2C) for a particular AADT ranges (e.g., 35,000-45,000), finding other (e.g., < 25,000) irrelevant.	Evaluation study / Survey	Filtering + Report
	B4) Objectives and operational environment	System objectives, performance, integration with multimodal features and new emerging technologies	1. Main reason(s) for ATCS implementation	1. Agency reason for implementation of an ATCS (e.g., handle high day-to-day variations in traffic, to handle special events).	1. Each agency, which deployed an ATCS, has a different motivation for it (e.g., handling oversaturated conditions, handling special events etc.). By providing this sub-category one can investigate major reasons for ATCS installation, for various types of agencies.	Evaluation study / Survey	Report
			2. ATCS performance assessment	2. Agency representatives perspective on various performance measures reduction resulting from deployed ATCS	2. For each deployed ATCS, based on the agency representative assessment this category will provide option to provide an assessment of how particular brand performs on contrary to results that are obtained from evaluation study.	Survey	Report
			3. ATCS multimodal environment	3. Agency representatives perceptive on utilization of multimodal features by deployed ATCS	3-4. Each deployed ATCS to various extent utilize/integrates with multimodal features or emerging technologies. Within these two categories, user of AT2C can retrieve data regarding each deployed system and utilization/integration with these features. This is important to note since some deployed brands may show inability of operating/integrating.	Survey	Report

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
B) Deployed ATCS	B4) Objectives and operational environment	System objectives, performance, integration with multimodal features and new emerging technologies	4. ATCS integration with emerging technologies	4. Agency representatives perspective on integration of deployed ATCS with emerging technologies	3-4. Each deployed ATCS to various extent utilize/integrates with multimodal features or emerging technologies. Within these two categories, user of AT2C can retrieve data regarding each deployed system and utilization/integration with these features. This is important to note since some deployed brands may show inability of operating/integrating.	Survey	Report
	B5) Communications and detection of ATCS	Communication and detection technology that is utilized by deployed ATCS	1. Transmission media	1. Transmission media that is used for communication between central ATCSs hardware/software and field traffic controllers	1-3. Each deployment and particular system require specific detection layout, technology and communication infrastructure between central ATCSs and field traffic controllers. By introducing these categories, one is able to investigate more on requirements for each ATCS brand.	Evaluation study / Survey	Report
			2. Detection layout	2. Detection layout defines detectors position relative to the stop-line		Evaluation study / Survey	Report
			3. Detection technology	3. Detection technology defines which technology is utilized for traffic flow detection		Evaluation study / Survey	Report
	B6) Previously traffic control system	Signal operation and control type prior to ATCS deployment	1. Previous signal type of operation	1. Type of signal operation is defined as a coordinated, isolated (non-coordinated) and mixed	1-2. Type of signal operation among control type represents the most influential factor for determining the magnitude of benefits that can be achieved with an ATCS implementation. In cases where previous technology was not so responsive and adjustable to various traffic fluctuations, more benefits can be expected when an ATCS technology is deployed. These categories servers to identify a particular type of signal operation and control for each deployment.	Evaluation study / Survey	Filtering + Report
			2. Previous control type on ATCS deployed corridor/network	2. We define control type as a semi-actuated, fully actuated, etc.		Evaluation study / Survey	Filtering + Report

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
B) Deployed ATCS	B6) Previously deployed system	Signal operation and control type prior to ATCS deployment	3. When the last time signals were retimed on examined network?	3. When the last time signals were retimed on examined network?	3-4. In addition to sub-categories 1 and 2, benefits of an ATCS deployment are also affected by signal retiming frequency. It is obvious that outdated signal timing plans changed with one ATCS solution will lead to higher benefits than in the case that signals were retimed just before ATCS deployment. By introducing this sub-category user of future (AT)2C is able to perform filtering only for those developments where signal retiming was performed relatively frequently, finding other, outdated signal timing plans, irrelevant.	Evaluation study / Survey	Filtering + Report
			4. Previous signals fine tuning frequency	4. Frequency of signals fine tuning		Evaluation study / Survey	Filtering + Report
	B7) Capital and maintenance costs	Costs associated with installation, operation and maintenance of an ATCS deployment	1. Average costs of installation per intersection	1. Average costs of installation per intersection including all costs associated with ATCS deployment	1-3. Costs associated with the deployment of an ATCS among system maintenance costs represent one of the obstacles why agencies are not widely implementing these systems. Total costs can be classified as installation costs (including replacement of detection type, signal controller etc.), installation costs of ATCS software and license and maintenance costs. The user of future (AT)2C can perform filtering based on certain budget projection within own agency in order to assess costs of implementation particular ATCS.	Evaluation study / Survey	Report
			2. Costs of installation of ATCS software per intersection	2. Cost of installation of ATCS software includes installation costs and licensing costs of installation		Evaluation study / Survey	Report
			3. Average maintenance costs of ATCS per intersection per year	3. Maintenance costs include both, hardware and software maintenance costs, including infrastructure needs required by ATCS operation		Evaluation study / Survey	Report
	B8) System monitoring and operating	ATCS monitoring and operating and system life cycle	1. Which parameters can be adjusted in real time?	1. Fine-tuning of signal timing parameters (e.g., splits, offset) in real time from perspective of ATCS is necessary to achieve highest benefits from a deployed ATCS	1. Here, for each deployment, it is identified which parameters can be monitored and tuned in real time by ATCS. In cases where an ATCS has the flexibility to adjust more parameters, higher benefits of the system can be achieved. It is interesting to investigate which set of parameters are adjustable, in real-time manner, for each ATCSs brand.	Evaluation study / Survey	Report

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
B) Deployed ATCS	B8) System monitoring and operating	ATCS monitoring and operating and system life cycle	2. ATCS system life cycle	2. ATCS system life cycle (i.e., life span).	2. This category is introduced in order to assess from system installation timeline and agency representatives, life cycle of deployed ATCS.	Evaluation study / Survey	Report

2.3 Section C) Evaluation Information

In this section we examine data categories related to the process of evaluating a deployed ATSC. Three main categories are identified which are then further expanded in sub-categories as shown in Figure 4. For each ATCS deployment these sub-categories will be identified, and this will establish a basis for a fair mutual comparison of evaluation results (see Section D) in the Assessment Tool for Adaptive Traffic Control ((AT)2C).
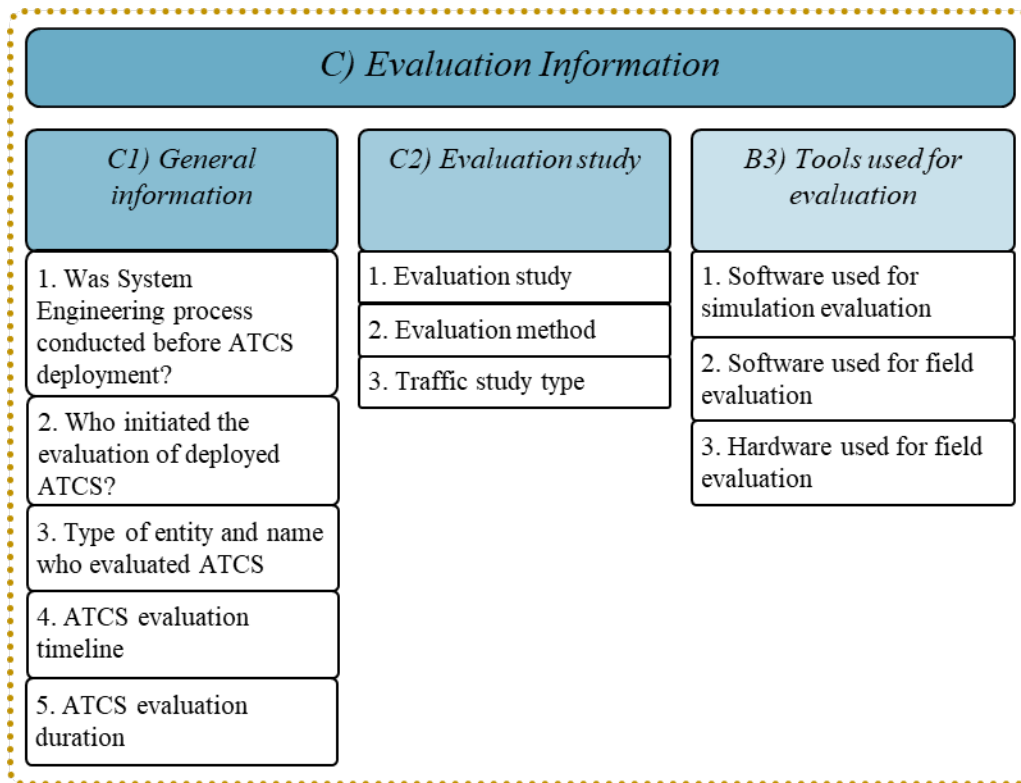
Figure 52 Categories and sub-categories within section C

Detailed explanation of categories and sub-categories, their justifications, and means of data collection are presented in Table 3.

Table 3 Definitions, justifications, process of gathering and usage of data within Section C

SECTION C							
Section	**Category**	**Category explanation**	**Sub-category**	**Definition of sub-category**	**Justification**	**Obtained from**	**Used for**
C) Evaluation information	C1) General information	Regarding subject who perform evaluation and evaluation time line	1. Was system-engineering process conducted prior ATCS deployment?	1. System engineering process represent an effective guidance for deploying ATCS agencies on procurement, selection, maintenance and evaluation of system.	Based on guidelines for system engineering process regarding ATCS, need for an evaluation study can be defined. It can be shown that when system engineering process is conducted, higher magnitude of benefits resulting deployment is achieved.	Evaluation study / Survey	Filtering + Report
			2. Who initiated the evaluation of deployed ATCS?	2. Entity who initiate evaluation study for deploying ATCS	2. This category in addition to previous and following, can show relationship between entities in the process of system evaluation. User of AT2C might be interested to investigate evaluation studies initiated by particular entity (e.g., University).	Evaluation study / Survey	Filtering + Report
			3. Who performed evaluation?	3. Evaluation studies are performed by different bodies, research institutes, contactors, vendors, or even in-house (within agency which operate deployed ATCS).	3. Since evaluation studies are performed by different entities, one may find of particular interest to filter only evaluation studies, which are conducted by research institutes. Moreover, the user of future (AT2C might be interested to investigate does reported benefits of the system are in correlation with a body who performed an evaluation.	Evaluation study / Survey	Filtering + Report
			3.1. Name of performing evaluation agency	3.1 Name of agency that performed evaluation.	3.1 In addition, to claim above, user of future (AT2C might want to perform filtering only for particular agencies (e.g., Midwest Research Institute).	Evaluation study / Survey	Filtering
			4. Evaluation timeline	4. Time component of each evaluation study consists of three points in time, a date when evaluation started (before), a date when ATCS started operating, and a date when evaluation was finished (after).	4. Since each evaluation study has its timeline, a future user of (AT2C may want to filter out various scenarios. For example, a user may be interested only in evaluations performed in the last five years (e.g. 2012-2017), finding older ones outdated.	Evaluation study / Survey	Filtering + Report
			5. Evaluation duration	5. Represent time span from moment when evaluation was initiated and completed, from the data collection standpoint.	5. Provided as filtering category this variable serves as an attempt to differentiate evaluation studies that lasted for several days from those that lasted couple of months in order to isolate potential effects of changes in traffic conditions.	Evaluation study / Survey	Filtering

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
C) Evaluation information	C2) Evaluation study	Study type, evaluation method and technique used for evaluation	1. Evaluation type	1. Two main evaluation types, found in the literature are: field evaluation or evaluation in simulation environment.	1. Field evaluation studies are usually based on floating car data or similar field recordings of traffic performance. Results of these studies depend on prevailing conditions in traffic flow for the particular days when the study was performed. On the other hand, simulation evaluation studies are performed in traffic simulation tools and give a larger variety of traffic data. Simulation studies are sometimes not trusted but sometimes they include a rigorous calibration and validation. By providing this sub-category to a user of (AT)2C we give him/her flexibility to filter out those evaluations which may not be in his/hers area of interest.	Evaluation study / Survey	Filtering + Report
			2. Evaluation method	2. Evaluation methods used in evaluation studies are 'before-after' or 'on-off'.	2. The evaluation method 'before and after' is based on examination of conditions on a certain network before deployment of ATCS and after a certain period of time, usually when ATCS is fully operative. 'On-off' method relies on a comparison of system performance when the system is running under ATCS (On) and when the ATCS is turned off (Off), in which case background TOD plans are usually turned on. So, the 'On-off' method gives evaluators a chance to control when each of the mode will be effective thus giving them more control over the experiments when traffic varies significantly.	Evaluation study / Survey	Filtering + Report
			3. Traffic study type	3. Evaluation of an ATCS deployment is conducted through study of various traffic performance measures (e.g., travel time, intersection delay, etc.).	3. There are several traffic studies types that can be performed to assess benefits of a particular system. We introduce this category to investigate traffic studies conducted during evaluation process.	Evaluation study / Survey	Report
			4. Technique used for data collection	4. Data collection techniques used in evaluation studies are floating car data, probe vehicle data, detector data, manual observations etc.			

Section	Category	Category explanation	Sub-category	Definition of sub-category	Justification	Obtained from	Used for
C) Evaluation information	C3) Tools used for evaluation	Depending on evaluation study type there is numerous tools that were used for evaluation	1. Software used for simulation evaluation	1. In case where study is performed in simulation environment, depending which ATCS system is evaluated, various simulation tools are used.	1. There are various traffic simulation tools used for simulation of ATCS (e.g., VISSIM, Aimsun, Corsim, etc.). This sub-category essentially provides a user of the (AT)2C additional information on the simulation tool used during evaluation.	Evaluation study / Survey	Report
			2. Software used for field evaluation	2. In evaluation studies (especially travel time studies) various software are used to process vehicle trajectories to obtain data, and performance measures of interest.	2-3. Various field evaluation studies require software and hardware for data processing (PC Travel, i-Track, Jamar TDC-12, etc.). For each such an evaluation study we want to document use of specific software and hardware, as available in the evaluation description.	Evaluation study / Survey	Report
			3. Hardware used for field evaluation	3. In some evaluation studies, data processing is conducted using special hardware.			

2.4 Section D) Evaluation results

In this section we examine the data categories related to the evaluation results of the ATCS deployments. Two categories are identified related to the evaluation results reported for weekdays and special traffic events. Weekday results are grouped in three distinctive peak periods (AM, Mid-day, and PM), while depending on a period when a special event was evaluated times for special events could fall in other time periods such as AM off-peak period, weekend etc.

Within each category, sub-categories are identified, and they present common performance measures used in the process of evaluation an ATCS deployment (shown in Figure 5). It needs to be stated here that during the course of this project it is very likely that we will add new performance measures in sub-categories, considering that new evaluation studies may use some of the new (high-resolution) performance metrics.

Figure 53 Categories and sub-categories within section D

Detailed explanation of categories and sub-categories, justifications, means of data collection and usage are presented in Table 4.

Table 4 Definitions, justifications, process of gathering and usage of data within Section D

<table>
<tr><th colspan="8" style="text-align:center">SECTION D</th></tr>
<tr>
<th>Section</th>
<th>Category</th>
<th>Category explanation</th>
<th>Sub-category</th>
<th>Definition of sub-category</th>
<th>Justification</th>
<th>Obtained from</th>
<th>Used for</th>
</tr>
<tr>
<td>D) Evaluation results</td>
<td>D1) Weekday

D2) Special events

D3) Weekend</td>
<td>Evaluation results or effects of deployed ATCS that are reported for typical weekday traffic for three peak hour periods (AM, Midday and PM) will be examined.</td>
<td>Some of performance measures identified in evaluation studies so far:

1. Delay
2. Travel Time (TT)
3. Number of stops reduction
4. Side street delay
5. Queue lengths
6. Split failure
7. Number of crashes
8. Number of conflicts
9. Fuel consumption
10. Emissions per pollutant
11. Transit travel time</td>
<td>1. Delay represents difference in travel times between actual and free-flow traffic conditions
2. Travel time represents time that is necessary for vehicle to pass certain road segment under prevailing traffic conditions
3. Vehicle is considered as stopped when its speed is less than threshold value (different studies consider different values).
4. Side-street delay, see definition in point 1 above.
5. Queue lengths represent average number of vehicles in lane during initiation of green signal indication.
6. Split failure represent number of splits during examined period that were not able to accommodate traffic demand.
7-8 Number of crashes/conflicts that occur on particular network for particular time period (reported by type).
9. Fuel consumption is either estimated (using some tools to process vehicular trajectories, see C3)2; or derived from traffic simulation software, see C3)1.) or measured with sophisticated instruments.
10. Emissions per pollutant, in the same way as fuel consumption, this performance measure is either estimated or measured with sophisticated instruments.
11. Travel time for transit vehicles, see definition at point 2.</td>
<td>In order to assess the magnitude of benefits that arise from ATCS deployment, within this category/sub-category, various performance measures are examined. We found that: three peak periods (AM, Mid-day and PM peak hour) for average weekday (Tuesday, Wednesday, etc.), one period (scenario) for special events (usually oversaturated conditions on Friday PM peak hour), and one period during weekend traffic, are appropriate number of intervals for a comprehensive assessment of the system performance. List of performance measures examined in this framework is based on conducted literature review from ATCS evaluation studies. Since each evaluation study relay on various performance measures, similar performance measures were combined into a single category, for the sake of practicality. Practically, if study A examined control delay which is derived from floating car data and study B examined network delay derived from simulation software (e.g., VISSIM), the user of future (AT)2C will be able to compare the benefits in terms of delay reduction for these two deployments. For further clarification, a user of (AT)2C can investigate details of the evaluation studies (obtained through the filtering process).</td>
<td>Evaluation study / Survey</td>
<td>Filtering + Report</td>
</tr>
</table>

APPENDIX C   SURVEY FOR DEPLOYING ATCS AGENCIES

Welcome to the Survey on Adaptive Traffic Control Systems

The Transportation Research Board's National Cooperative Highway Research Program (NCHRP) has commissioned a study on Adaptive Traffic Control Systems (ATCS). The goal of the research is to provide details on various ATCS deployments and evaluation studies. Each deployment is unique due to factors such as the agency's own circumstances, characteristics of the network where the system has been deployed, system functionalities, and similar. Also, each evaluation is done slightly differently regarding techniques, procedures, available hardware and software, data retrieved, etc. Thus, this research seeks to properly classify all of the relevant information so that future ATCS user know what they can expect, based on a number of their potential criteria. To accomplish this goal, we seek to collect the most important factors influencing deployments and reported benefits of the ATCSs deployed across the United States. The answers from this survey will be used to populate a database which will be publicly accessible through a standalone Microsoft Excel spreadsheet. This database will help practitioners to retrieve information by filtering and cross-referencing all of the identified categories related to the ATCS deployments and reported benefits.

Please note that the survey consists of two parts: (i) Section A – Agency Details (estimated time to respond to this section is around 10 minutes) and (ii) Sections B, C and D (estimated time to respond to these questions in case that your agency has a single ATCS deployment and a single evaluation study is around 35 minutes). Also please note that you can respond to Section D (Evaluation results) in two ways: 1. by uploading an evaluation report, or 2. by filling corresponding answers for each evaluation time period. If you chose the first option (to upload an evaluation study report) we will review the report and enter all relevant data in the database on your behalf.

Please complete all of the sections as accurately and thoroughly as possible. We appreciate your participation.

Please provide your contact information.

Note: If you are taking this survey more than once to enter data for your 2nd, 3rd, etc. ATCS deployment/evaluation, please just fill in the field 'Company' below, leave the other fields blank, and skip the questions until the Section B – Details of Deployed ATCS, where you can enter remaining data.

1. Contact information

Name:

Company:

Address:

City/Town:

State/Province:

ZIP/Postal code:

Country:

Phone number:

Email address:

Section A - Agency Details

This section covers the information about your agency. This information will help our team to identify how your agency's organization, capabilities, and budgeting impact ATCS deployment and performance.

A1- Basic Agency Information

2. Select the best description for your agency.
   a. City government
   b. County government
   c. State government
   d. Regional organization (e.g., metropolitan planning organization)
   e. Federal government
   f. Consultant
   g. Other (please specify):_____

3. What is an approximate cumulative length of the road network under jurisdiction of your agency?
   a. <200 miles
   b. 200–800 miles
   c. 800–1,200 miles
   d. 1,200–1,800 miles
   e. 1,800–2,400 miles
   f. >2,400 miles
   g. If you know the exact number of miles, please specify:_____

4. How many traffic signals does your agency operate?
   a. <100
   b. 100–200
   c. 200–300
   d. 300–400
   e. 400–500
   f. >500
   g. If you know the exact amount of signals, please specify:_____

5. How many of the traffic signals operated by your agency are coordinated?
   a. <50
   b. 50–80
   c. 80–130
   d. 130–200
   e. 200–300
   f. >300
   g. If you know the exact number of these signals, please specify:_____

A2 - Agency Workforce

6. Please specify number of employees, for each category below (both in-house and outsourced), who work on operations and maintenance of traffic signals for your agency.
    a. Number of managers:_____
    b. Number of engineers:_____
    c. Number of controller technicians:_____
    d. Number of other technicians:_____

7. Please specify an approximate number of hours in training (in person-hours) that each of the staff categories (given below) received in order to understand and operate the ATCS deployed by your agency.
    a. Hours of training for managers:_____
    b. Hours of training for engineers:_____
    c. Hours of training for controller technicians:_____
    d. Hours of training for technicians :_____

8. Do you have enough staff to operate and maintain the ATCSs day-to-day operations?
    a. Yes
    b. No – how much more do you need and what type? _____

A3 - Agency Budgeting

9. What is estimated annual budget for signal operations and maintenance in your agency?
    a. <$100,000
    b. $100,000–500,000
    c. $500,000–1,000,000
    d. $1,000,000–2,000,000
    e. >$2,000,000
    f. If you know the exact amount of funding, please specify:_____

10. What is estimated annual funding for capital traffic-signal-related projects?
    a. <$100,000
    b. $100,000–500,000
    c. $500,000–1,000,000
    d. $1,000,000–2,000,000
    e. >$2,000,000
    f. If you know exact amount of funding, please specify:_____

Section B – Details of Deployed ATCSs

This section asks for information about deployed ATCS – e.g. type of the area where the ATCS is deployed, reasons for deploying an ATCS, traffic control system which was used before the ATCS deployment, and similar.

B1 - Deployed ATCSs

11. How many ATCSs does your agency operate?
    a. None
    b. One
    c. Two
    d. Three
    e. Four
    f. Five
    g. Six
    h. Seven
    i. Eight
    j. More than eight
    k. If more than eight, please specify: _____

12. If your agency operates multiple ATCSs are they all using the same ATCS technology?
    a. Yes
    b. No

13. If operating more than one ATCS technology, how would you describe your operating experiences with multiple ATCS brands?
    a. Very difficult, please explain _____
    b. Difficult, please explain _____
    c. Normal
    d. Relatively easy
    e. Easy

14. If your agency operates multiple ATCSs, how are these multiple systems monitored?
    a. All from one central platform (e.g., ATMS)
    b. Individually (each system has its own platform for monitoring)
    c. Other (please specify):_____

B2 – Selection method and Installation of the ATCS

Note:
Please keep in mind that the following questions are related to __a particular ATCS deployment__. You will be informed later how to provide data for your other deployed ATCSs and corresponding evaluation study(ies), in the case your agency runs multiple ATCSs.

15. Which brand of ATCS has been deployed at your agency? Please select from drop-down list.
In online version of survey, drop-down list includes following systems: ACDSS, ACS Lite, Balance/Epics, Centracs Adaptive, InSync, ITACA, Kadence, LADOT ATCS, Marlin, MAC, MaxAdapt, MOTION, NWS Voyage, OPAC, QuicTrac, RHODES, SCATS, SCOOT, SURTRAC, SynchroGreen, Transparity, UTOPIA, Xtelligent, VS-PLUS and Other (please specify).

16. What method was used to select the deployed ATCS?
    a. Competitive bidding
    b. Sole source

    c.   Other (please describe): _____

Definitions:

Competitive bidding – Deploying agency provides in-depth specifications of projects and invite vendors (contractors) to bid. Competitive bidding aims at obtaining goods and services at the lowest prices by stimulating competition.

Sole Source – Deploying agency procure the particular (unique) system which is justified to be the only one that fulfills requirements.

17. ATCS installation timeline:
    a.   When did the ATCS installation start (year/month)? _____/_____
    b.   By what time was the ATCS fully operational (year/month)? _____/_____

18. Has the agency faced any unpredicted delays during ATCS installation, and if yes how long?
    a.   No
    b.   Yes, the installation was delayed for ____ months.

19. If the installation delays were experienced, what where the main reasons for such delays? Select all that apply
    a.   Poor coordination between installation vendor and the agency
    b.   Agency's internal issues (e.g., budgetary problems, staff retention, delay of the other relevant projects)
    c.   Technical problems (e.g., detection, communications, equipment). Please specify:_____
    d.   Others (please specify):_____

20. What is the current status of the deployed ATCS?
    a.   Fully operational
    b.   Partially operational (i.e., system is used with a limited scope or together with TOD plans)
    c.   Partially decommissioned (technology still there but not used; can be easily switched ON in future)
    d.   Fully decommissioned

21. If the ATCS is decommissioned (partially or fully), what are the main reasons? Select all that apply.
    a.   Detection and communication problems
    b.   Lack of required expertise and other institutional challenges
    c.   Incompatibility with other technologies and applications (e.g., ramp metering, TSP, pedestrian operations)
    d.   System not compatible with agency's expectations and practice (e.g. too many complaint calls)
    e.   No operational benefits achieved
    f.   Other, please describe: _____

22. Besides your own agency, was any other entity involved in the decision making and implementation of the ATCS? Please select all that apply.
    a.   Metropolitan planning agency
    b.   Other DOT/County/City authority
    c.   Public community group
    d.   Public transit agency
    e.   Nobody else
    f.   Other (please specify):_____

B3 – Area Coverage of the ATCS

23. In which city is this ATCS deployed?

Please specify: _____

24. Which of the following area types is the best match of the area where your ATCS is deployed? Please note that each type of answer is illustrated in the following photos.

a. Urbanized area or Central Business District (CBD)
b. Urban area
c. Suburban area
d. Rural area

A) Urbanized area/CBD   B) Urban area   C) Suburban area   D) Rural area

25. What is the number of signals operating under ATCS?

a. Less than five
b. Five–10
c. 10–15
d. 15–20
e. 20–30
f. >30
g. If you know exact number of signals, please specify:_____

26. What is an approximate length (in miles) of the network under ATCS?

a. Less than three miles
b. Three to six miles
c. Six to nine miles
d. Nine to twelve miles
e. Twelve than fifteen miles
f. More than fifteen miles
g. If you know exact number of miles, please specify:_____

27. What is an approximate AADT on the busiest road where the ATCS is deployed?

a. ≤ 25,000
b. 25,000 – 35,000
c. 35,000-45,000
d. 45,000-55,000
e. >55,000
f. N.A.

B4 – Objectives and Operational Environment of the ATCS

28. What were the main reasons to deploy ATCS? Select all that apply.

a. Handling over-saturated traffic conditions
b. Improving conditions of traffic flow
c. Handling traffic during special events

d. Handling high day-to-day and within-a-day traffic variability
e. Handling conflicts between vehicular traffic and other modes
f. Serving as an early deplorer of innovative technology
g. Availability of funding for capital intelligent transportation system (ITS) projects
h. Expecting significant operational savings and a high benefit cost ratio
i. Improving safety and reducing the number of crashes
j. Other (please specify):_____

29. For the set of performance measures given below, to which extent would you agree that the deployed ATCS met your agency's expectations?

	Strongly disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly agree (5)	N/A
Delay	o	o	o	o	o	o
Side street delay	o	o	o	o	o	o
Travel time	o	o	o	o	o	o
Number of stops	o	o	o	o	o	o
Side street number of stops	o	o	o	o	o	o
Queue length	o	o	o	o	o	o
Side street queue length	o	o	o	o	o	o
Number of crashes	o	o	o	o	o	o
Number of conflicts	o	o	o	o	o	o
Emissions	o	o	o	o	o	o
Fuel consumption	o	o	o	o	o	o
Pedestrian delay	o	o	o	o	o	o
Transit delay	o	o	o	o	o	o
Transit travel time	o	o	o	o	o	o
Other (please specify):	o	o	o	o	o	o

30. If the deployed ATCS operates in multimodal environment, to which extent is the ATCS utilized to help with multimodal operations?

	Not utilized (1)	(2)	Partially utilized (3)	(4)	Fully utilized (5)	N/A
Rail road operations	o	o	o	o	o	o
Transit signal priority	o	o	o	o	o	o
Pedestrian accommodation	o	o	o	o	o	o
Bicycle accommodation	o	o	o	o	o	o
Other (please specify):	o	o	o	o	o	o

31. To which extent are the existing appurtenances of your ATCS integrated with new and emerging technologies (see below)?

	Not integrated (1)	(2)	Partially integrated (3)	(4)	Fully integrated (5)	N/A
High-resolution data analyzing and reporting (e.g., ATMS)	o	o	o	o	o	o
Vehicle to infrastructure (V2I) communication	o	o	o	o	o	o
Vehicle to vehicle (V2V) communication	o	o	o	o	o	o
Other (please specify):	o	o	o	o	o	o

B5 – Communications and Detection of the ATCS

32. What type of transmission media does your ATCS use for communication between central hardware/software and field traffic controllers? Select all that apply

   a. Twisted pair
   b. Telephone line
   c. Coaxial cable
   d. Fiber optic
   e. Microwave (terrestrial or satellite)
   f. Wireless (application protocol or broadband systems)
   g. Other (please specify):_____

33. What type of detection layout do you use for your ATCS? Select all that apply.

   a. Stop-line detectors
   b. Near-stop-line (upstream from stop line from 32ft to 200ft)
   c. Upstream (mid-block) detectors
   d. Upstream (far-side) detectors (located at the exit point of the upstream intersection)
   e. Other (please specify):_____

34. What type of detection technology do you use for your ATCS? Select all that apply.

   a. Inductive loops
   b. Video detection
   c. Microwave radar detection
   d. Other (please specify):_____

B6 – Previous Traffic Control System

35. What was the previous type of traffic signal operations on the network where the ATCS is deployed?
    a. TOD - Fixed
    b. TOD - Semi-actuated
    c. TOD - Fully actuated
    d. Other (please specify):_____

36. How much coordinated were the signals before the ATCS was deployed? Previously, the signal network (now under the ATCS) was predominantly:
    a. Isolated
    b. Coordinated
       If Mixed please specify % of coordinated: _____
37. Approximately, when was the last time that the signals under the ATCS were before the ATCS was deployed (year/month)? _____/_____
38. How frequently were the signals under the ATCS "fine-tuned" before the ATCS deployment?
    a. Every few months (less than three)
    b. Every three to six months
    c. Every six to nine months
    d. Every nine to twelve months
    e. Every year or less frequently
    f. Not applicable

B7 - Capital and Maintenance Costs of the ATCS

39. Please specify approximate costs associated with the ATCS deployment:
    a. What was the total average cost of installation per intersection? _____
    b. What was the cost of installation of ATCS software (licensing and similar)? _____
    c. What was the average maintenance cost of ATCS per year (provide your best estimate)? _____

40. Are the operations and maintenance costs of deployed ATCS (expressed as costs per intersection) higher or lower than your previous TOD traffic control?
    a. ATCS costs are lower, by approximately: _____
    b. Almost the same
    c. ATCS costs are higher, by approximately: _____

B8 - System Monitoring and Operations

41. How understandable are working principles of your ATCS to you and your colleagues?
    a. Very understandable
    b. Understandable
    c. OK
    d. Not very understandable
    e. Not understandable at all

42. Which signal timing parameters can be adjusted in real time with your deployed ATCS? Select all that apply.
    a. Splits
    b. Offsets
    c. Cycle length
    d. Phase sequence
    e. Other (please specify): _____

43. What is your expected ATCS life cycle?
    a. Less than five years
    b. Five to ten years
    c. Ten to fifteen years
    d. Fifteen to twenty years
    e. More than twenty years

Section C - Evaluation Information

This section covers information about the conducted evaluation studies, such as: who performed the evaluation, how it was done, what methods and tools were used, etc.

C1 - General Information about Evaluation Study

44. How many evaluation studies were performed for the deployed ATCS?
    a. None
    b. One
    c. Two
    d. If more than two, please specify: _____

Please note:
If for deployed ATCS evaluation study was not conducted, skip following questions and depending on number of ATCS deployments within agency, redo the survey from Section B) Details of Deployed ATCSs.
If for deployed ATCS you have more than one evaluation study, please take this and following survey part (Section C and Section D) again in order to report data for other evaluations.

44. Was a System Engineering process conducted before your ATCS was deployed?
    a. Yes, please specify name of the consultant _____
    b. No

45. Who initiated the evaluation of the deployed ATCS?
    a. Consulting firm
    b. Consultant who performed System Engineering process
    c. ATCS (installation) vendor
    d. Deploying agency (In-house)
    e. University (Academia institution)
    f. Research Institute

      g.   Other (please specify):_____

46. What type of entity evaluated the quality of ATCS performance?
      h.   Consulting firm
      i.   ATCS (installation) vendor
      j.   Deploying agency (In-house)
      k.   University (Academia institution)
      l.   Research Institute
      m. Other (please specify):_____

47. Please specify the name(s) of entity(ies) who performed the evaluation: _____
48. ATCS evaluation timeline:
      a.   When did the evaluation start (year/month)? _____/_____
      b.   By what time was the evaluation completed (year/month)? _____/_____

C2 - Evaluation Study

49. Which evaluation type was undertaken? Select all that apply.
      a.   Field evaluation
      b.   Simulation evaluation
      c.   Other (please specify): _____

50. Which evaluation method was used? Select all that apply.
      a.   Before-after
      b.   On-off
      c.   Other (please specify): _____

Definitions:
Before-after – A "before" study is done before the ATCS is installed in the field, usually while a conventional (TOD) traffic signal control is functional. An "after" study is done once the ATCS is deployed and an adaptive regime replaces TOD control. There is usually a several-month time span between 'before' and 'after' evaluation. Traffic conditions during 'before' and 'after' studies can be significantly different if there are strong seasonal traffic fluctuations.
On-off – Both "on" and "off" studies are done after an ATCS is deployed in the field. In the case of "On" study the ATCS is turned on and the signals work in a (fully) adaptive mode. Logically, in the case of "Off" study the ATCS's adaptive operations are turned off and a set of background TOD plans (mimicking before ATCS conditions) control traffic. In the case of On-off study seasonal traffic variations can be avoided (if both studies are done within the same traffic season) but the issue could be that the background TOD plans working in "Off" study may not be identical to the true TOD plans in effect before the ATCS was deployed.

51. Which traffic data collection methods, techniques, and data sources were used for the conducted evaluation studies? Please, select all that apply (not all of the options are applicable for all studies).

	Floating car data	Average car data	'Max.' car data	INRIX	RITIS	TomTom	Video cameras	Bluetooth sensors	Loop detectors	Manual counts	Survey	N/A
Volume studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Travel time studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Delay studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Density studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Accident studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Freight studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Transit studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pedestrian studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental impact studies	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Other (please specify): _____

52. While conducting evaluation study did you use the same data collection methods, techniques, and data sources for all time periods (e.g. AM, MidDay, PM) for all of the scenarios (e.g., before and after)?
    a. Yes
    b. No, please specify which evaluation periods used different data collection methods (including data collection methods): _____

C3 - Tools Used for Evaluation

53. Which software tools were used for simulation evaluation? Select all that apply.
    a. PTV Vissim
    b. Aimsun
    c. CORSIM
    d. PARAMICS
    e. SimTraffic
    f. Other (please specify):_____
    g. No simulation study was done

54. Which software were used for field data collection and processing? Select all that apply.
    a. PC Travel
    b. i-travel
    c. MICRO 2
    d. GPS Kit Pro
    e. Other (please specify):_____

55. Which hardware were used for field data collection and processing? Select all that apply.
    a. JAMAR counting/delay device
    b. Laptop with GPS device
    c. Camera with GPS device
    d. Cell phone
    e. Other (please specify):_____

56. Which of the following best describes the geometrical shape of the network where the ATCS was deployed?
Please note that each answer choice is illustrated in the photos below.
    a. Single corridor
    b. Two intersecting corridors
    c. Grid
    d. Irregular urban network
    e. Mixed (or Other)
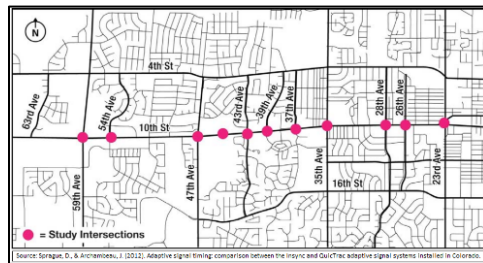
A) Single corridor   B) Two intersecting corridors   C) Grid
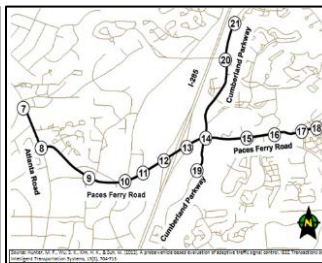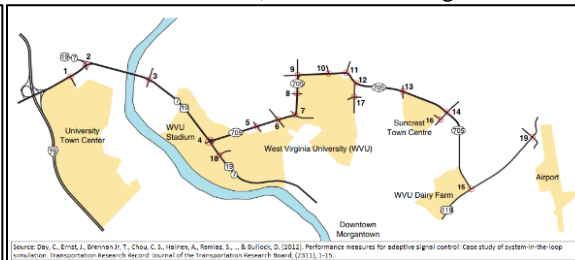
D) Irregular urban network   E) Mixed (or Other)

57. For which of the following traffic conditions was the evaluation performed? Select all that apply.
    a. Regular conditions (i.e. Typical weekday, Mon-Thu)
    b. Special conditions (i.e. Oversaturation, Weekends, Special events, Incidents, Preemption)
    c. Other (please specify):_____

58. For which of the following time periods was evaluation performed? Select all that apply.
    a. AM peak hour
    b. Midday peak hour
    c. PM peak hour
    d. Other (please specify):_____

Section D - Evaluation Results

Please note that you can respond to this section in two ways: 1. by uploading an evaluation report, or 2. by filling corresponding answers for each evaluation time period. If you chose the first option (to upload an evaluation study report) we will review the report and enter all relevant data in the database on your behalf.

59. Do you prefer to upload an evaluation report or do you want to enter the evaluation results on your own?
    a. I want to upload evaluation report
    b. I want to enter evaluation results

D1 – Uploading the Evaluation Report(s)

60. Please upload your evaluation report(s) here. ____

61. Were you able to successfully upload the evaluation report(s)?
    a. Yes
    b. No – we will contact you soon via an e-mail to arrange delivery of the evaluation report(s).

D2 – Reporting the Evaluation Results

This section covers the results of the evaluation studies. Note that it is only possible to provide answers in a <u>sequential manner </u>- once you select traffic scenario (e.g. typical conditions), you will be asked to select a time period for which you want to report the evaluation results. Once done with the selected interval, you will be returned to <u>the same</u> question (Q62) to complete the information for the other intervals, and then for different traffic conditions, etc.

62. Please select for which traffic conditions and time periods you want to report evaluation data?
    a. Regular conditions – AM peak hour
    b. Regular conditions – Midday peak hour
    c. Regular conditions – PM peak hour
    d. Regular conditions – 'Other' time period
    e. Special conditions – AM peak hour
    f. Special conditions – Midday peak hour
    g. Special conditions – PM peak hour
    h. Special conditions – 'Other' time period
    i. 'Other' conditions – AM peak hour
    j. 'Other' conditions – Midday peak hour
    k. 'Other' conditions – PM peak hour
    l. 'Other' conditions – 'Other' time period

<u>**Please note:**</u>
In order to avoid creating robust survey in this survey form (MS Word) for the part of reporting evaluation results, we are listing three distinctive type of questions (evaluation report forms for -single corridor, -two intersecting corridors and -irregular/grid/mixed network type). Please note that number of questions in this section depend on traffic conditions (e.g., regular conditions – typical weekday) part of the day (e.g., AM peak hour) and afore mentioned three types of the network (e.g., two intersecting corridors) when evaluation was performed. Since total number of different evaluation scenarios will lead to creating robust survey, we would like from you to multiply these questions depending on needed number. For example, your agency conducted evaluation on deployed ATCS on a single corridor, during typical weekday, for AM, Midday and PM peak hour, you will copy questions number 63 and 64, two more times and report the data for remaining evaluation periods.

Reported benefits for a typical weekday, - AM peak hour, and a -single corridor

Please note here that there are essentially two approaches of conducting an evaluation study, by evaluating performance of deployed ATCS on individual route(s) or on the entire network. For each time period, there is an option to report the results based on the evaluation approach (route or network). If you are reporting results only for route evaluations, feel free to skip a question on the network evaluation, and vice versa.

63. What are the value of performance measures for "before" ("off") and "after" ("on") evaluations for the AM peak hour on defined route(s)?
<u>Please note</u> that our assumption is that evaluation was done on the main corridor (C1) for both directions (d1 and d2). In the following fields, we would like you to enter values for each performance measure in the following manner. If on a corridor C1 respective delays for directions d1 and d2 were 100s and 101s for "before" ("off") case,

and 50s, 51s for "after" ("on") case, then the record of this performance should look like this: d1: 100s/50s; d2: 101s/51s. Please repeat the same recording logic for each of the relevant performance measures given below.

    a.   Delay: _____

    b.   Side street delay: _____

    c.   Travel time: _____

    d.   Number of stops: _____

    e.   Side street number of stops: _____

    f.   Queue length: _____

    g.   Side street queue length: _____

    h.   Number of crashes: _____

    i.   Number of conflicts: _____

    j.   Emissions per pollutant (HC, CO, CO_2, NOx, VOC) : _____

    k.   Fuel consumption : _____

    l.   Pedestrian delay: _____

    m.   Transit delay: _____

    n.   Transit travel time: _____

    o.   Other (please specify_____

64. What are the values of performance measures for "before" ("off") and "after" ("on") evaluations for the AM peak hour on a network level?

<u>Please note</u> that our assumption is that evaluation was done on a network level, by examining all roads which are under particular ATCS. In the following fields, we would like you to enter values for each performance measure in the following manner. If on a network average (aggregated) delay was 100s for "before" ("off") case, and 50s for "after" ("on") case, then the record of this performance should look be noted: 100s/50s. Please repeat the same recording logic for each of the relevant performance measures given below.

    a.   Delay: _____

    b.   Side street delay: _____

    c.   Travel time: _____

    d.   Number of stops: _____

    e.   Side street number of stops: _____

    f.   Queue length: _____

    g.   Side street queue length: _____

    h.   Number of crashes: _____

    i.   Number of conflicts: _____

    j.   Emissions per pollutant (HC, CO, CO_2, NOx, VOC) : _____

    k.   Fuel consumption : _____

    l.   Pedestrian delay: _____

    m.   Transit delay: _____

    n.   Transit travel time: _____

    o.   Other (please specify_____

Reported benefits for a typical weekday, - AM peak hour, and a –two intersecting corridors

Please note here that there are essentially two approaches of conducting an evaluation study, by evaluating performance of deployed ATCS on individual route(s) or on the entire network. For each time period, there is an option to report the results based on the evaluation approach (route or network). If you are reporting results only for route evaluations, feel free to skip a question on the network evaluation, and vice versa.

65. What are the value of performance measures for "before" ("off") and "after" ("on") evaluations for the AM peak hour on defined route(s)?

<u>Please note</u> that our assumption is that the evaluation was completed for both intersecting corridors (C1 and C2) and in all four directions (C1- d1; d2, and C2- d3; d4). In the following fields, we would like you

to enter values for each
performance measure in the following manner. E.g., if on corridor C1, in directions d1 and d2, delays were 100s, 101s for a "before" ("off") case and 50s, 51s for an "after" ("on") case, and on C2, in directions d3 and d4, delays were 200s, 201s for a "before" ("off") case, and 150s, 151s for an "after" ("on") case, then a corresponding delay record should look like: C1- d1: 100/50s; d2: 101s/51s, C2- d3: 200s/150s; d4: 201s/151s. Please repeat the same recording logic for each of the relevant performance measures given below.

    a. Delay: _____
    b. Side street delay: _____
    c. Travel time: _____
    d. Number of stops: _____
    e. Side street number of stops: _____
    f. Queue length: _____
    g. Side street queue length: _____
    h. Number of crashes: _____
    i. Number of conflicts: _____
    j. Emissions per pollutant (HC, CO, CO2, NOx, VOC) : _____
    k. Fuel consumption : _____
    l. Pedestrian delay: _____
    m. Transit delay: _____
    n. Transit travel time: _____
    o. Other (please specify_____

66. What are the values of performance measures for "before" ("off") and "after" ("on") evaluations for the AM peak hour on a network level?
<u>Please note</u> that our assumption is that evaluation was done on a network level, by examining all roads which are under particular ATCS. In the following fields, we would like you to enter values for each performance measure in the following manner. If on a network average (aggregated) delay was 100s for "before" ("off") case, and 50s for "after" ("on") case, then the record of this performance should look be noted: 100s/50s. Please repeat the same recording logic for each of the relevant performance measures given below.

    a. Delay: _____
    b. Side street delay: _____
    c. Travel time: _____
    d. Number of stops: _____
    e. Side street number of stops: _____
    f. Queue length: _____
    g. Side street queue length: _____
    h. Number of crashes: _____
    i. Number of conflicts: _____
    j. Emissions per pollutant (HC, CO, CO2, NOx, VOC) : _____
    k. Fuel consumption : _____
    l. Pedestrian delay: _____
    m. Transit delay: _____
    n. Transit travel time: _____
    o. Other (please specify_____

Reported benefits for a typical weekday, - AM peak hour, and a -Irregular/Grid/Mixed network

Please note here that there are essentially two approaches of conducting an evaluation study, by evaluating performance of deployed ATCS on individual route(s) or on the entire network. For each time period, there is an option to report the results based on the evaluation approach (route or network). If you are reporting results only for route evaluations, feel free to skip a question on the network evaluation, and vice versa.

67. What are the value of performance measures for "before" ("off") and "after" ("on") evaluations for the AM peak hour on defined route(s)?

Please note our assumption is that the evaluation was done for multiple routes and in multiple directions (R1- d1; d2, R2- d3; d4, R3- d5; d6, R4- d7; d8…). In the following fields, we would like you to enter the values for each of the performance measures in the following manner. For example, on route R1, in directions d1 and d2, delays were 100s, 101s for the "before" ("off") case, and 50s, 51s for the "after" ("on") case. Then, the similar corresponding values on R2, in the directions d3 and d4, were 200s/201s for the "before" ("off") case and 150s/151s for the "after" ("on") case. On R3, in the directions d5 and d6, delays were 300s/301s for the "before" ("off") case and 250s/251s for the "after" ("on") case. In this situation, the corresponding record should look like: R1- d1: 100/50s; d2: 01s/51s, R2- d3: 200s/150s; d4: 201s/151s, R3- d5: 300s/301s; d6: 301s/251s. Please repeat the same recording logic for each of the relevant performance measures given below.

    a.   Delay: _____
    b.   Side street delay: _____
    c.   Travel time: _____
    d.   Number of stops: _____
    e.   Side street number of stops: _____
    f.   Queue length: _____
    g.   Side street queue length: _____
    h.   Number of crashes: _____
    i.   Number of conflicts: _____
    j.   Emissions per pollutant (HC, CO, CO2, NOx, VOC) : _____
    k.   Fuel consumption : _____
    l.   Pedestrian delay: _____
    m.   Transit delay: _____
    n.   Transit travel time: _____
    o.   Other (please specify_____

68. What are the values of performance measures for "before" ("off") and "after" ("on") evaluations for the AM peak hour on a network level?

Please note that our assumption is that evaluation was done on a network level, by examining all roads which are under particular ATCS. In the following fields, we would like you to enter values for each performance measure in the following manner. If on a network average (aggregated) delay was 100s for "before" ("off") case, and 50s for "after" ("on") case, then the record of this performance should look be noted: 100s/50s. Please repeat the same recording logic for each of the relevant performance measures given below.

    a.   Delay: _____
    b.   Side street delay: _____
    c.   Travel time: _____
    d.   Number of stops: _____
    e.   Side street number of stops: _____
    f.   Queue length: _____
    g.   Side street queue length: _____
    h.   Number of crashes: _____
    i.   Number of conflicts: _____
    j.   Emissions per pollutant (HC, CO, CO2, NOx, VOC) : _____
    k.   Fuel consumption : _____
    l.   Pedestrian delay: _____
    m.   Transit delay: _____
    n.   Transit travel time: _____
    o.   Other (please specify_____

APPENDIX D   LIST OF DEPLOYING ATCS AGENCIES

	List of surveyed agencies in US	
#	**Name of the agency**	**Deployed ATCS**
1	Ada County, ID	InSync
2	Aiken, SC	InSync
3	Albuquerque, NM	InSync
4	Allentown, PA	InSync
5	Anaheim, CA	Multiple
6	Ann Arbor, MI	SCOOT
7	Arcadia, CA	ACDSS
8	Arlington, VA	SCOOT
9	Atlanta, GA	Multiple
10	Augusta, GA	InSync
11	Aurora, IL	InSync
12	Austin, TX	Multiple
13	Bala Cynwyd, PA	InSync
14	Balmville, NY	InSync
15	Baltimore, MD	InSync
16	Bartow, FL	InSync
17	Bay County, FL	InSync
18	Bayonne Bridge, NY	ACDSS
19	Baytown, TX	Multiple
20	Beachwood, OH	Centracs
21	Beaumont, TX	InSync
22	Beaverton, OR	SCATS
23	Bellevue, WA	SCATS
24	Bellmawr, NJ	InSync
25	Belton, TX	InSync
26	Bernalillo County, NM	Centracs
27	Bernalillo, NM	InSync
28	Birmingham, AL	SCATS
29	Bloomfield, NJ	InSync
30	Boca Raton, FL	SynchroGreen
31	Bradford Woods, PA	InSync
32	Brevard County, FL	SynchroGreen
33	Bristol, PA	InSync
34	Bristol, VA	InSync

35	Brookfield, WI	InSync
36	Brooklawn, NJ	InSync
37	Brooklyn Bridge, NY	ACDSS
38	Brooklyn Park, MD	SynchroGreen
39	Broward County, FL	InSync
40	Brunswick, OH	Centracs
41	Bucks County, PA	Centracs
42	Buffalo Grove, IL	InSync
43	California Department of Transportation — District 7, CA	LA ATCS
44	Camden, NJ	InSync
45	Canon City, CO	QuicTrac
46	Cape Girardeau, MO	InSync
47	Carlisle, PA	InSync
48	Cary, NC	OPAC
49	Casper, WY	NWS Voyage
50	Concord, NC	Centracs
51	Chalfont, PA	InSync
52	Charlottesville, VA	InSync
53	Chattanooga, TN	InSync
54	Cheltenham, PA	InSync
55	Chesapeake, VA	OPAC
56	Chula Vista, CA	SCATS
57	Claremore, OK	InSync
58	Clearwater, FL	InSync
59	Clemson, SC	InSync
60	Clermont County, OH	Centracs
61	Cobb County, GA	SCATS
62	Coeur d'Alene, ID	Multiple
63	Collegeville Borough, PA	InSync
64	Collier County, FL	Multiple
65	Columbia County, GA	InSync
66	Columbia, MO	InSync
67	Columbia, SC	InSync
68	Columbus, OH	Centracs
69	Concord Township, PA	InSync
70	Concordville, PA	InSync
71	Coronado, CA	SCOOT
72	Cranberry Township, PA	Centracs
73	Culver City, CA	LA ATCS
74	Dallas, GA	InSync
75	Danbury, CT	Centracs

76	Daytona Beach, FL	InSync
77	DeLand, FL	InSync
78	Delaware Department of Transportation, DE	SCATS
79	Dillsburg, PA	InSync
80	Doylestown, PA	InSync
81	Dresher, PA	InSync
82	Dunedin, FL	InSync
83	Durham, NC	SCATS
84	East Whiteland Township, PA	InSync
85	Elkins, WV	InSync
86	Essex Junction, VT	InSync
87	Evans, GA	InSync
88	Evansdale, IA	InSync
89	Exmore, VA	InSync
90	Fairfax County, VA	InSync
91	Fairfield, CA	InSync
92	Farmington, NM	InSync
93	Fauquier Co, VA	InSync
94	FDR Drive, NY	ACDSS
95	Fishers, IN	InSync
96	Flint, MI	InSync
97	Florida DOT District 4, FL	SCATS
98	Flushing, NY	ACDSS
99	Folsom, CA	Centracs
100	Fort Collins, CO	Centracs
101	Fort Lee, NJ	Centracs
102	Fort Meade, MD	InSync
103	Fort Pierce, FL	Centracs
104	Fort Worth, TX	InSync
105	Frederick County, VA	InSync
106	Fulton County, GA	Centracs
107	Gainesville, FL	InSync
108	Galveston, TX	SynchroGreen
109	Gastonia, NC	Centracs
110	Genesee County, MI	InSync
111	Gillette, WY	NWS Voyage
112	Gilroy, CA	LA ATCS
113	Glenwood Springs, CO	Transparity
114	Grapevine, TX	InSync
115	Greeley, CO	Multiple
116	Greenfield, WI	InSync

117	Greenwood Village, CO	Centracs
118	Gresham, OR	SCATS
119	Gulf Shores, AL	Centracs
120	Hanover Borough, PA	InSync
121	Harrisburg, PA	InSync
122	Hattiesburg, MS	SCOOT
123	Havertown, PA	InSync
124	Hayward, CA	Multiple
125	Hernando County, FL	Centracs
126	Hesperia, CA	InSync
127	Hillsboro, OR	InSync
128	Huntington, WV	Centracs
129	Huntsville, AL	SCATS
130	Indian River County, FL	Centracs
131	Islip, NY	InSync
132	Jackson, NJ	InSync
133	Jacksonville, NC	Centracs
134	Jane, MO	InSync
135	Jersey City, NJ	SCATS
136	John's Creek, GA	Centracs
137	Joplin, MO	InSync
138	Kansas City, MO	InSync
139	King of Prussia, PA	InSync
140	Lake Monroe, FL	InSync
141	Lakewood Ranch, FL	InSync
142	Lamar, CO	QuicTrac
143	Lancaster, PA	InSync
144	Lansdale, PA	InSync
145	Lawrence Township, NJ	InSync
146	Leawood, KS	InSync
147	Lebanon County, PA	ACS-Lite
148	Lee's Summit	InSync
149	Lenexa, KS	InSync
150	Lewisburg, PA	InSync
151	Lexington, KY	InSync
152	Liberty, MO	InSync
153	Lima, OH	InSync
154	Little Rock, AR	InSync
155	Long Beach, CA	LA ATCS
156	Long Island, NY	InSync
157	Longmont, CO	InSync

158	Longview, TX	ACS Lite
159	Los Angeles Department of Transportation, CA	LA ATCS
160	Louisville, KY	InSync
161	Lower Gwynedd Township, PA	InSync
162	Lynchburg, VA	InSync
163	MacDill Air Force Base, FL	InSync
164	Madison, WI	Centracs
165	Manhattan, KS	InSync
166	Manhattan, NY	ACDSS
167	Marietta, GA	SCATS
168	Martin County, FL	Centracs
169	Maryland, MD	Centracs
170	Mason, OH	Centracs
171	Maumelle, AR	InSync
172	McCandless Township, PA	InSync
173	Meadowlands, NJ	SCATS
174	Medford, OR	InSync
175	Menlo Park, CA	Multiple
176	Mesa, AZ	Multiple
177	Miami-Dade County, FL	Multiple
178	Midland, TX	InSync
179	Milwaukee, WI	InSync
180	Minneapolis, MN	SCOOT
181	Minnesota Department of Transportation, MN	SCATS
182	Mishawaka, IN	Centracs
183	Missouri, MO	InSync
184	Monroeville, PA	InSync
185	Monterey, CA	SCOOT
186	Montgomery County, MD	Multiple
187	Montgomery, AL	SCATS
188	Montgomery, OH	Centracs
189	Montgomeryville, PA	InSync
190	Moorhead, MN	NWS Voyage
191	Mount Juliet, TN	InSync
192	Mount Pleasant, SC	InSync
193	Mountain View	InSync
194	Mundelein, IL	InSync
195	Murrysville, PA	InSync
196	New Brunswick, NJ	InSync
197	New Mexico, NM	Centracs
198	Newport News, VA	Multiple

199	Newton, KS	InSync
200	Newtown, PA	InSync
201	Norristown, PA	InSync
202	North Canton, OH	Centracs
203	North Richland Hills, TX	InSync
204	Oakland County, MI	SCATS
205	Ocala, FL	InSync
206	Oceanside, CA	QuicTrac
207	Onley, VA	InSync
208	Orange Beach, AL	Centracs
209	Orange County, CA	Centracs
210	Orange County, FL	Multiple
211	Orlando, FL	Multiple
212	Overland Park, KS	Multiple
213	Oviedo, FL	InSync
214	Oxnard, CA	SCOOT
215	Pacifica, CA	InSync
216	Palm Beach County, FL	InSync
217	Panama City, FL	InSync
218	Park City, UT	SCATS
219	Pasadena, CA	SCATS
220	Pasco County, FL	Multiple
221	Patton Township, PA	Centracs
222	Peoria, AZ	InSync
223	Philadelphia, PA	Multiple
224	Pierce County, WA	Centracs
225	Pine Township, PA	InSync
226	Pinellas County, FL	Multiple
227	Pittsburgh, PA	Multiple
228	Plymouth Township, PA	InSync
229	Pooler, GA	InSync
230	Port St. Lucie, FL	InSync
231	Portland, OR	Multiple
232	Pottstown, PA	InSync
233	Pueblo, CO	QuicTrac
234	Puyallup, WA	InSync
235	Raymore, MO	InSync
236	Redmond, OR	SCATS
237	Reedy Creek District, FL	SCOOT
238	Renton, WA	SCOOT
239	Richardson, TX	InSync

240	Richmond, VA	InSync
241	Road Commission for Oakland County, MI	SCATS
242	Roanoke, VA	InSync
243	Rogers, AR	InSync
244	Roseville, CA	SynchroGreen
245	Roswell, GA	SCOOT
246	Sacramento County, CA	Centracs
247	Saint Paul, MN	Centracs
248	Saint Petersburg, FL	InSync
249	Salem, VA	InSync
250	Salinas, CA	InSync
251	Sammamish, WA	InSync
252	San Diego, CA	Multiple
253	San Jose, CA	Multiple
254	San Leandro, CA	KADENCE
255	San Marcos, CA	QuicTrac
256	San Ramon, CA	InSync
257	Sandy Springs, GA	SCOOT
258	Santa Barbara, CA	SCOOT
259	Santa Clarita, CA	Transparity
260	Santa Rosa, CA	SCATS
261	Sarasota, FL	InSync
262	Savannah, GA	InSync
263	Seattle, WA	SCOOT
264	Seminole County, FL	Multiple
265	Sharonville, OH	Centracs
266	Sioux Falls, SD	InSync
267	Smyrna, DE	SCOOT
268	South Fayette Township, PA	InSync
269	Spokane, WA	Centracs
270	Springdale, AR	InSync
271	Springfield, MO	InSync
272	St. Albans, WV	InSync
273	St. Louis, MO	Multiple
274	Staten Island, NY	ACDSS
275	Staunton, VA	InSync
276	Stephens City, VA	InSync
277	Stockton, CA	InSync
278	Sunnyvale, CA	Multiple
279	Surprise, AZ	KADENCE
280	Tampa, FL	InSync

281	Teays Valley, WV	InSync
282	Temecula, CA	QuicTrac
283	Texarkana, AR	InSync
284	Toledo, OH	InSync
285	Topeka, KS	InSync
286	Tredyffrin Township, PA	InSync
287	Trenton, PA	InSync
288	Tucson, AZ	RHODES
289	Tuscaloosa, AL	SCOOT
290	City of Tyler, TX	NWS Voyage
291	Upper Dublin Township, PA	InSync
292	Upper Merion, PA	InSync
293	Upper Uwchlan, PA	Centracs
294	Utah Department of Transportation, UT	SCATS
295	Vacaville, CA	Multiple
296	Pickerington, OH	ACS Lite
297	Warminster Township, PA	InSync
298	Warrington, PA	InSync
299	Washington County, OR	SCATS
300	Washington DC, DC	QuicTrac
301	Washington State Department of Transportation, WA	RHODES
302	Waterbury, VT	InSync
303	Wauwatosa, WI	InSync
304	Waynesboro, VA	InSync
305	Wells, ME	Transparity
306	West Chester, PA	InSync
307	West Des Moines, IA	InSync
308	West Miami, FL	InSync
309	West Palm Beach, FL	InSync
310	West Virginia, WV	Centracs
311	Westlake, OH	Centracs
312	Wexford, PA	InSync
313	White Plains, NY	Multiple
314	Wichita, KS	InSync
315	Williamsburg, VA	InSync
316	Winchester, VA	InSync
317	Woburn, MA	InSync
318	Woodland Park, CO	QuicTrac
319	York, PA	InSync
320	Yorktown, VA	InSync
321	Morgantown, WV	ACSLite

322	Albany, NY	ACSLite
323	Houston, TX	ACSLite
324	Reston, VA	OPAC
325	Champaign, IL	SynchroGreen
326	City of Sugar Land, TX	SynchroGreen
327	Wakefield, MA	SynchroGreen
328	Dartmouth, MA	ACSLite
329	Framingham, MA	ACSLite
330	Burlington, MA	SynchroGreen
331	Lomita, CA	RHODES
332	Las Vegas, NV	SCATS
333	City of Glendale	Not specified
334	Phoenix, AZ	Not specified
335	Scottsdale, AZ	Not specified
336	Palo Alto, CA	Not specified
337	Johns Creek, GA	Not specified
338	City of Naperville, IL	Not specified
339	Libertyville, IL	Not specified
340	City of Greensburg, IN	Not specified
341	Augusta, ME	Not specified
342	City of Lebanon, MO	Not specified
343	City of Norman, OK	Not specified
344	City of Virginia Beach, VA	Not specified
345	Lynnwood, WA	SynchroGreen
346	Clark County, WA	SynchroGreen
List of surveyed agencies in Canada		
#	**Name of the agency**	**Deployed ATCS**
1	City of Red Deer, Canada	SCOOT
2	City of Toronto, Canada	Multiple
3	Halifax, NS Canada	SCOOT
4	Hamilton, ON Canada	Kadence
5	Windsor, ON Canada	Kadence
6	Langley, BC Canada	Centracs
7	Markham, ON, Canada	Centracs
8	Montreal, Canada	InSync
9	Red Deer, AB, Canada	SCOOT
10	Surrey, BC, Canada	MAC
11	City of Ottawa	Not specified

APPENDIX E   (AT)2C USER MANUAL

The Assessment Tool for Adaptive Traffic Control ((AT)2C) is developed to help practitioners and researchers in the identification, comparison, assessment, maintenance, and monitoring of appropriate Adaptive Traffic Control System (ATCS) technologies relative to the operations objectives. The tool is developed in MS Excel 2016 as a standalone tool which is intuitive and relatively easy to use. There are no specific hardware requirements for the tool. In order to perform filtering procedures one needs to install a version of MS Excel 2013 or later. The older versions of MS Excel may not have features necessary for pivot-charts and pivot-tables (e.g. time-line and regular slicers). The database for this this tool is populated with the data gathered using any of data collection methods (i.e., literature review, survey) so far conducted for this project.

The tool is designed in such way that can provide two type of analysis: (i) analyses of deploying ATCS environment and (ii) analyses of reported benefits resulting from ATCS deployments. These analyses are done by performing filtering of main categories defined for each ATCS deployment/evaluation. In the first case, the tool can be used as (AT)2C - Dashboard and in the second case, as (AT)2C - Filtering tool. In order to document all (AT)2C features, components and options this manual was developed. Instructions on how to perform both type of analyses and how to understand results obtained from such analysis are explained in detail in this manual.

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TABLE OF FIGURES

1. **Introduction**

The Assessment Tool for Adaptive Traffic Control ((AT)2C) is created to be used both as dashboard and as a filtering tool. Navigation through (AT)2C is established through the buttons where title of each button refers to a particular section of the (AT)2C.

(AT)2C – Dashboards – represents a set of interactive dashboards where a user can conduct analysis based on categories, often represented with slicers and similar tools. Each dashboard page contains a number of visuals (i.e. graphs) whose purpose is to visualize data from the database based on the user selection/filtering. Four dashboard pages are created within (AT)2C dashboard tool section:

5. Basic Agency Info
6. Operational Conditions
7. Infrastructure & Costs
8. Evaluation Details

Following sections of this manual describe details of each page with its corresponding elements. In order to access any of these pages, a user needs to select one of the buttons shown in Figure E1.

Figure E1 (AT)2C - Dashboards buttons

(AT)2C - Filtering tool – allows a user to perform more comprehensive analysis of the data (as opposed to relying on the visualizations predefined by the dashboard functionality). A goal of such analysis is to investigate benefits (in terms of benefits captured by various performance measures) from deploying an Adaptive Traffic Control System (ATCS). The filtering tool contains two pages:

1. Basic Results
2. Advanced Filtering

In the last section of this manual, each filtering page is described in detail, along with explanation on how to perform required analyses. Similarly to the Dashboard functionality of the (AT)2C tool, the filtering functionality is initiated by selecting corresponding buttons shown in Figure E2.

Figure E2 (AT)2C – Filtering tool buttons

Most of the data filtering actions, performed to retrieve relevant ATCS data, are done through the use of slicers within the MS Excel. A slicer is an object which allows visual data filtering from the corresponding database (defined when a slicer is established). For example, Figure E3 shows that by selecting one of the provided buttons (e.g., County government), a user can filter out all of the data relevant for county governments. A color of the slicer indicates a current filtering state (colorful = selected vs. colorless = unselected), as shown in the left and right parts of the Figure E3, respectively.
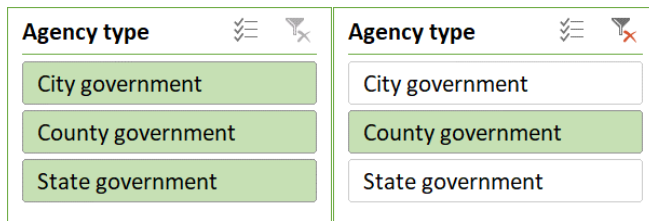
Figure E3 Slicer with no selection made (left), Slicer with selection (right)

In addition to the selection made in Figure E3, a user is able to select multiple interactive buttons. This is done by using a Multi-Select option (in the upper right corner of the left part of Figure E4. If needed to restore the slicer in its initial stage, a user can select an option Clear Filter (located in the upper right corner of the right part of Figure E4.
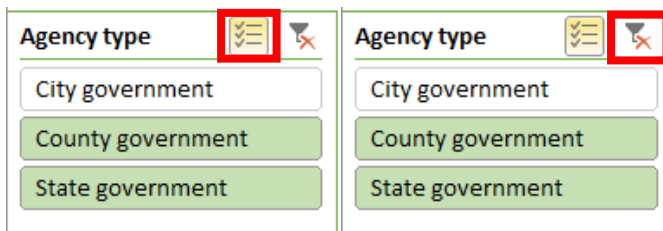
Figure E4 Multi-Select option (left), Clear Filter (right)

When it comes to time filtering of the data, the (AT)2C tool is equipped with multiple Timeline Slicers. This type of slicer works essentially in the same way as a standard slicer (see Figure E5). It is mainly used to filter out dates when particular event occurred (e.g., ATCSs was deployed / evaluated). Again, color of the slicer's bar indicates the current filtering status, if the bar is colorful (e.g. left side of Figure E2) it means that a particular period is taken in consideration. Otherwise the bar is colorless as shown in the right part of Figure E2. By dragging the slicer bar horizontally (left or right), a user can define a period of interest for which the data should be filtered out of the database, as shown in Figure E6.
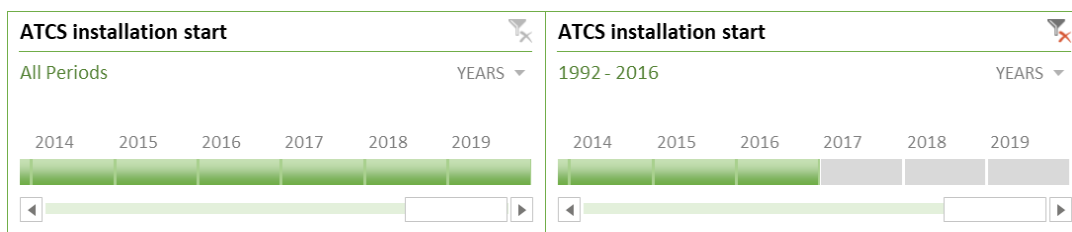
Figure E5 Timeline slicer with no selection (left), with selection (right)
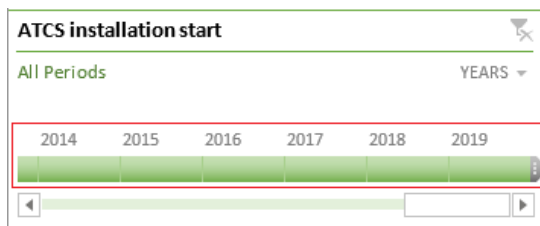
Figure E6 Timeline slicer, selection part of slicer

(AT)2C start up screen is presented in Figure E7, which facilitates a short version of the user manual, for handy use and quick reference of (AT)2C users. Once a user gets familiar with basic instructions there is a

navigational button (*Let's Start*) which directs him/her to the first (AT)2C Dashboard page. From that page, a user is able to navigate, by using similar navigation buttons, to any of other page of the (AT)2C.

Figure E7 (AT)2C – Start page

<u>Please keep in mind:</u>

The (AT)2C relies on a relatively robust database structure and it should be noted that some of the computational efforts may require several seconds before the data are visualized. Thus, it is important that a user is patient and understands that the performance of the visualization may be significantly restricted by the computational power and Excel's database accessing model.

A user should also note that by making every additional selection, a number of filtered instances decreases. A user may find useful to play with filtering options (e.g. by selecting Not specified filters under each filtering category or even clearing filters) to find out which of the filtering options are more important than the others.

There are no relational connections between filtering options on various (AT)2C dashboard sections/pages. This means that selections made within a dashboard page cause no modifications or updates on the other sections/pages.

It needs to be stated that the (AT)2C is designed as Excel Macro-Enabled Workbook. You will be asked once you open the (AT)2C to Enable Content (i.e., to enable macros). This step is necessary since some of the developed functionalities depend on created macros.

2. (AT)2C – Dashboards

2.1. Basic Agency Info

This section of the (AT)2C tool covers organizational context of the agency which deployed ATCS technology (e.g., number of employees, organizational structure of agency, preventive maintenance/operational budget etc.) and details of the installation process (e.g., installation delays, decommissioning and installation reasons and stakeholder coordination). A user can base their analyses on several criteria, such as agency type, deploying state, installation timeline, etc.

By selecting a filtering category/criterion, a user actually initiates a process where relevant data are retrieved from the database and visualized on the predefined charts and other visualization aids. Chart and table updates are done automatically based on the filtering selections. If no selection is made, the visual aids will display values based on all of the records in the (as shown in Figure E8).
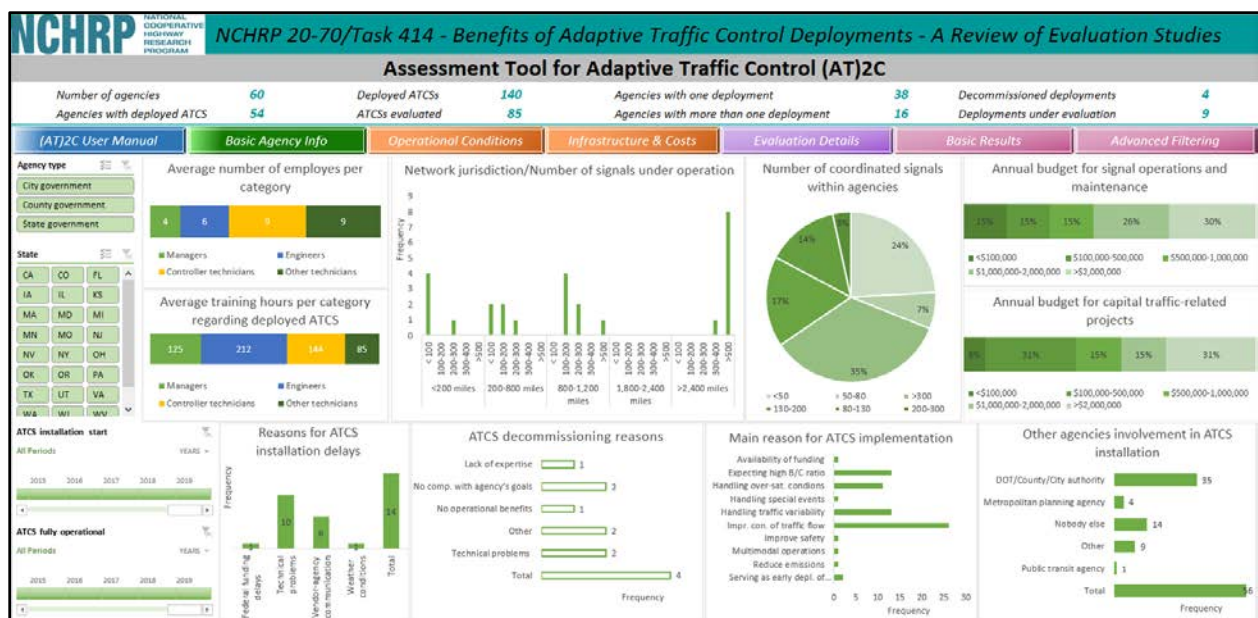
Figure E8 Basic agency information (Dashboard Page 1)

Example: Let us filter out all of the data on Basic Agency dashboard for all of the entities whose agency type is "State government". First, we would need to select "State government" in the slicer "Agency type", and then we would need to wait until the data are loaded and the graphs are updated, as shown in Figure E9.
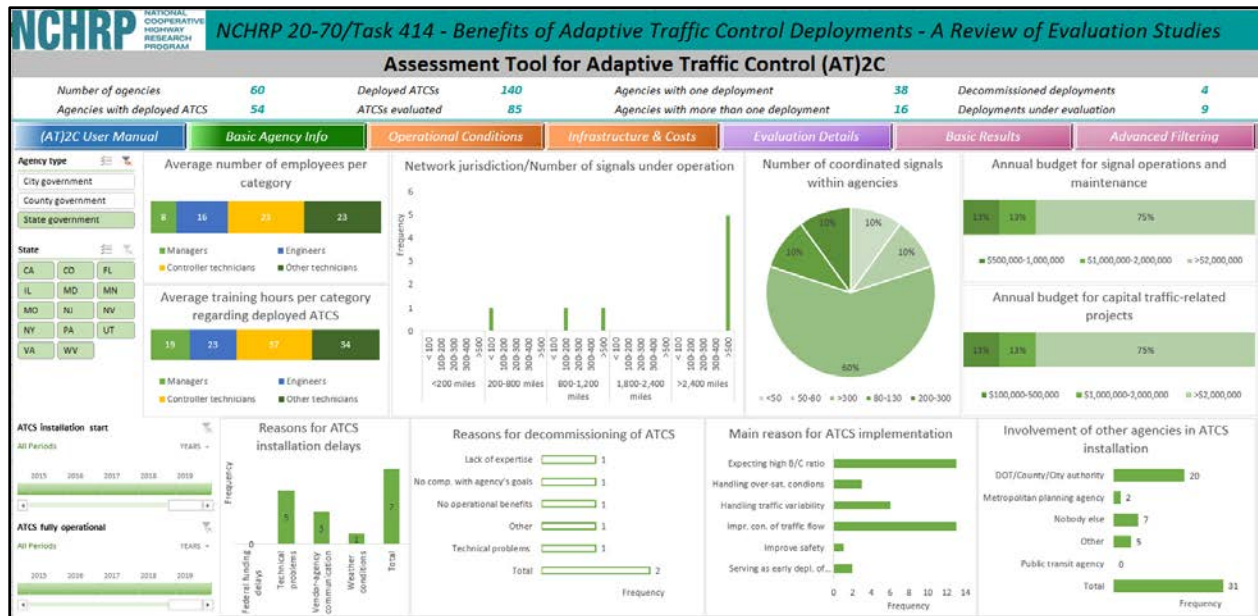
Figure E9 Basic agency information based on user selection

Several graph types are used to visualize basic agency information.

Pie charts are used to present number of coordinated signals within agency, as shown in Figure E10.
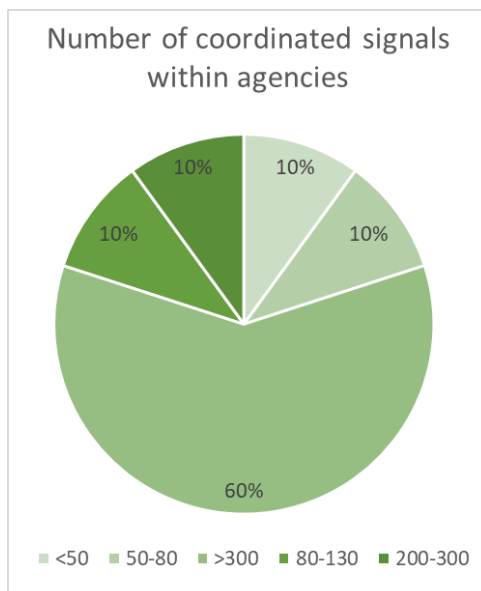
Figure E10 Number of coordinated signals within agency

Stacked bar charts are used to visualize agencies' workforces and budgets (as shown in Figures E11 and E12). Icons depict categories of the employees, where each icon indicates various categories (managers, engineers, controller technicians and other technicians, from bottom to the top). For each category there are two bars, one showing an average number of employees per agency (in this case, based on selection) and the other representing an average number of training hours received for a particular agency.

Agencies' budgets are defined by two bars where the first one (upper) shows an estimated budget for signal operations and maintenance, whereas the second (lower) shows an estimated budget for capital signal-related investments.

Average number of employees per category

Managers	Engineers	Controller technicians	Other technicians
8	16	23	23

■ Managers   ■ Engineers
■ Controller technicians   ■ Other technicians

Average training hours per category regarding deployed ATCS

Managers	Engineers	Controller technicians	Other technicians
19	23	37	34

■ Managers   ■ Engineers
■ Controller technicians   ■ Other technicians

Figure E11 Agencies workforce

Annual budget for signal operations and maintenance

13%	13%	75%

■ $500,000-1,000,000   ■ $1,000,000-2,000,000   ■ >$2,000,000

Annual budget for capital traffic-related projects

13%	13%	75%

■ $100,000-500,000   ■ $1,000,000-2,000,000   ■ >$2,000,000
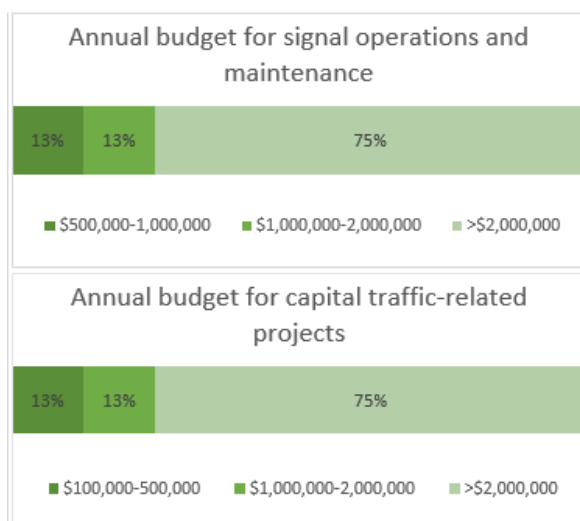
Figure E12 Agencies budget

Clustered columns charts are used, for example, to present network jurisdiction (network length in miles) of the agencies vs. number of signals under operation (as shown in Figure E13), or reasons for ATCS installation delays (as shown in Figures E14).
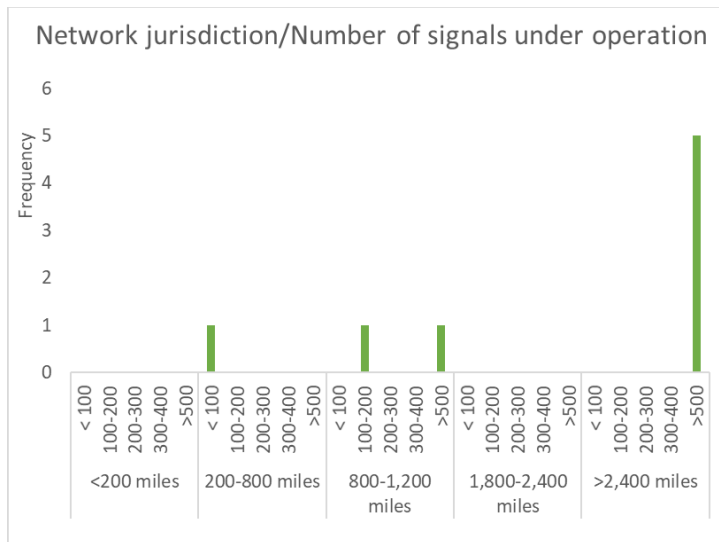
Figure E13 Road network coverage versus number of signals under operation
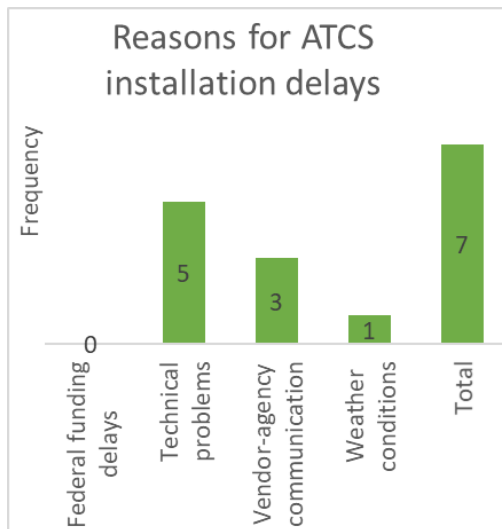
Figure E14 Reasons for ATCS installation delays

Stacked columns charts are used, for example, to visualize main reasons for ATCS implementation, stakeholder coordination (involvement of other agencies in decision process to install ATCS), as shown in Figures E15, E16 and E17.

Reasons for decommissioning of ATCS

Category	Frequency
Lack of expertise	1
No comp. with agency's goals	1
No operational benefits	1
Other	1
Technical problems	1
Total	2

Frequency
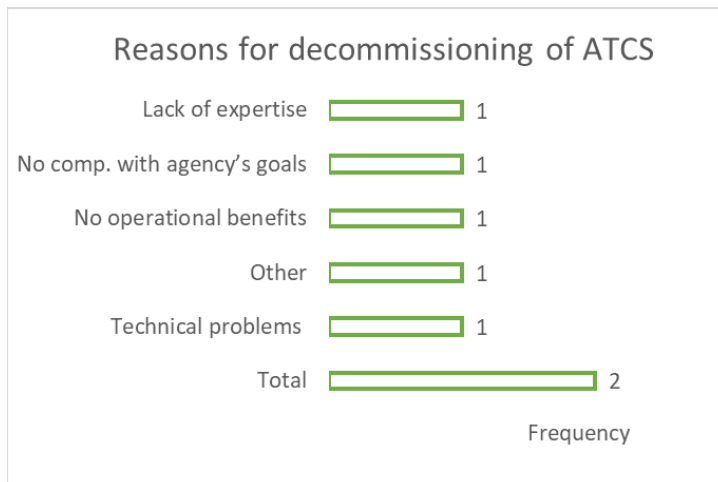
Figure E15 Main reasons for decommissioning ATCSs

Main reason for ATCS implementation

Category	Frequency
Expecting high B/C ratio	13
Handling over-sat. condions	3
Handling traffic variability	6
Impr. con. of traffic flow	13
Improve safety	1
Serving as early depl. of...	2

Frequency
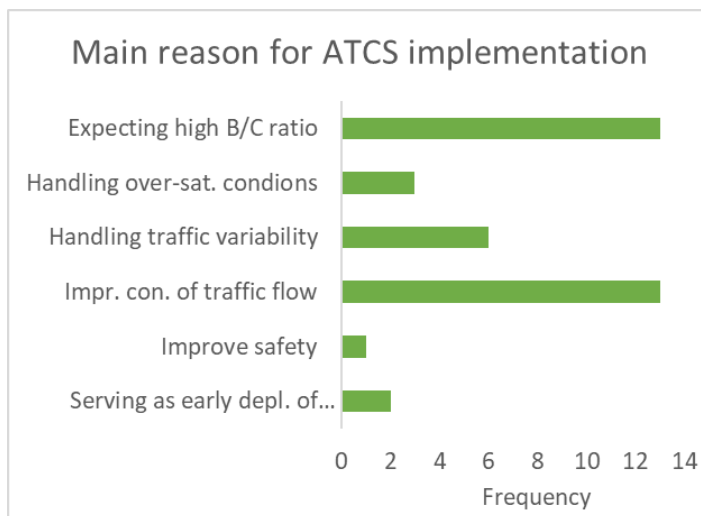
Figure E16 Main reasons for ATCS implementations

Involvement of other agencies in ATCS installation

Category	Frequency
DOT/County/City authority	20
Metropolitan planning agency	2
Nobody else	7
Other	5
Public transit agency	0
Total	31

Frequency
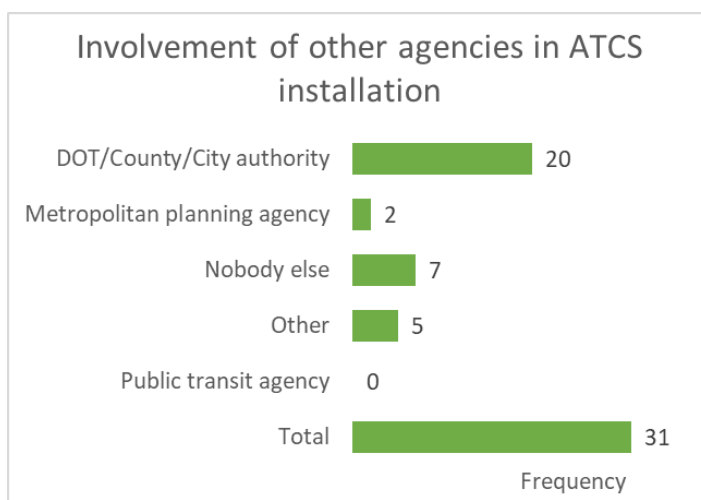
Figure E17 Involvement of other agencies in ATCS installation

2.2 Operational Conditions

Operational conditions, of an ATCS deployment, can be observed through a number of factors, such as: system capability (number of signals under operations, prevailing AADT of the main corridor(s), area and network type coverage), system monitoring and control, integration of existing appurtenances with new and emerging technology, multimodal operations, and alignment of agency's objectives with the ATCS' technology.

Analysis within this dashboard page is performed through a selection of particular ATCS brand(s) where for each selection visual aids are updated. In the case that no selection is made, visualizations are based on all of the records in the database (as shown in Figure E18).
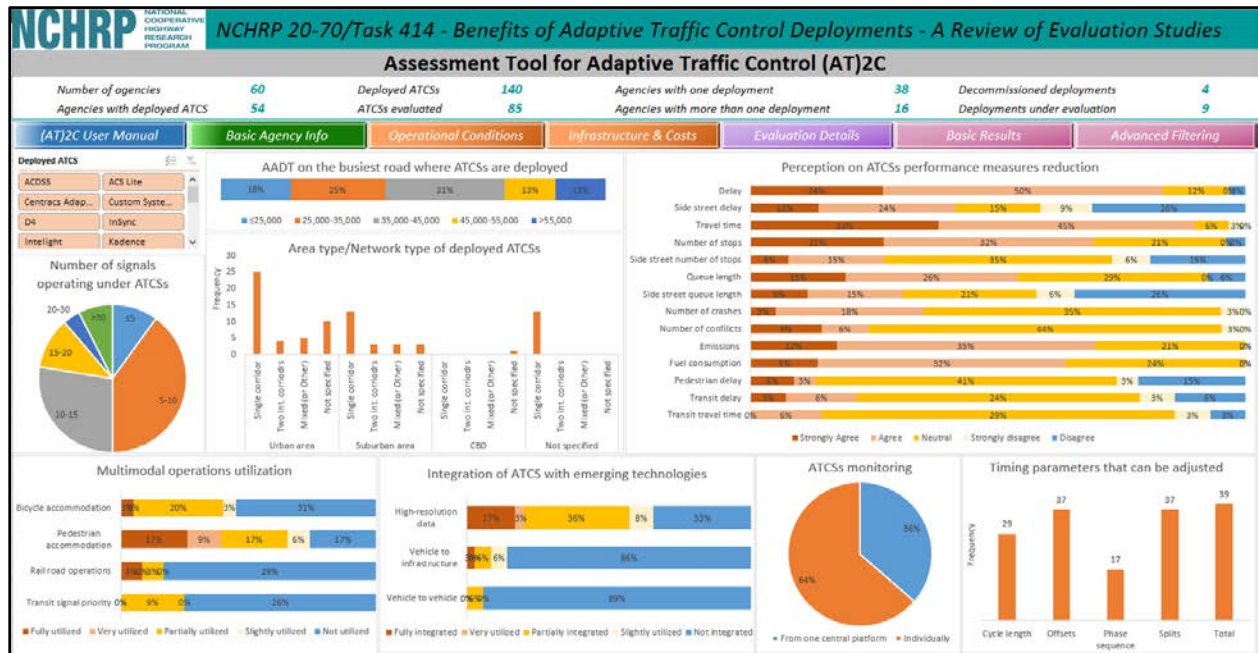
Figure E18 Operational conditions of ATCS deployment (Dashboard Page 2)

**Example:** Let us consider for example, operational conditions for three ATCSs brands (Centracs adaptive, InSync and Synchrogreen). By making an appropriate selection of these three systems (in the slicer "ATCS brand"), the charts will be updated and the main screen of this dashboard will look like shown in Figure E19.
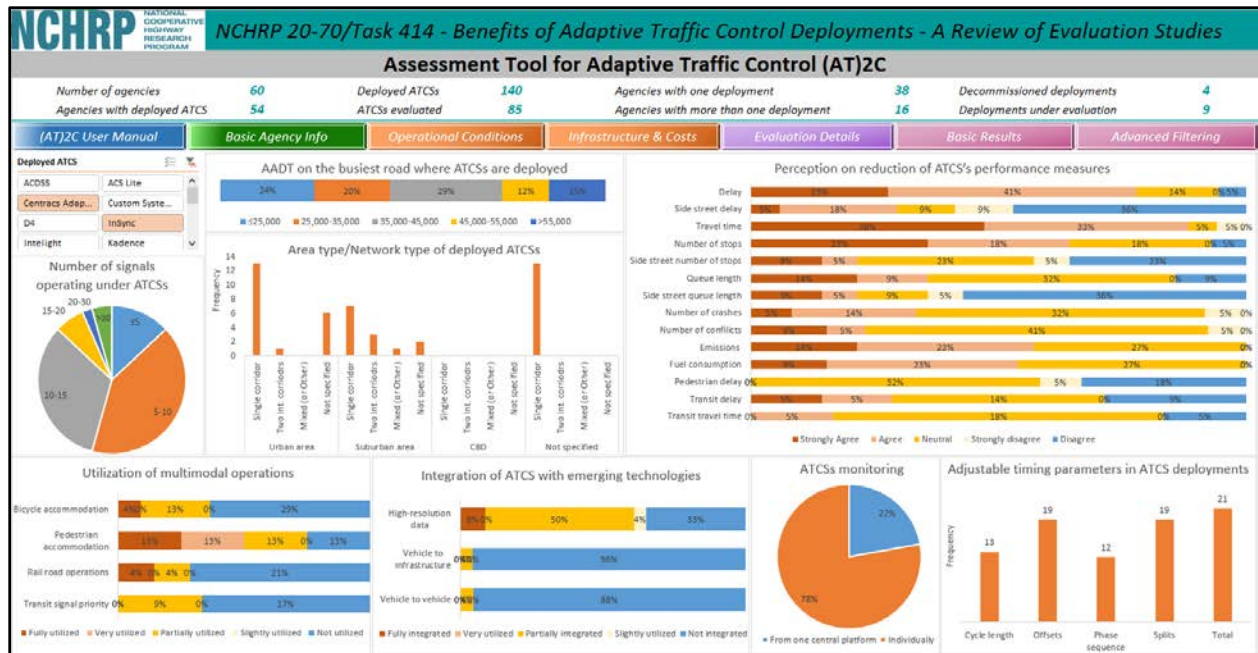
Figure E19 Operational conditions of ATCS deployment based on user selection

Following chart types are used to visualize operational conditions for this particular selection.

Pie charts are used to present number of signals operating under particular ATCS(s) brand(s) and how monitoring of such system(s) is performed (shown in Figures E20 and E21). It needs to be mentioned that insights on monitoring of ATCSs are based on responses of those agencies who have more than one deployed ATCSs. In those cases, agency's representatives were provided inputs on how each of these multiple operating brands were monitored.
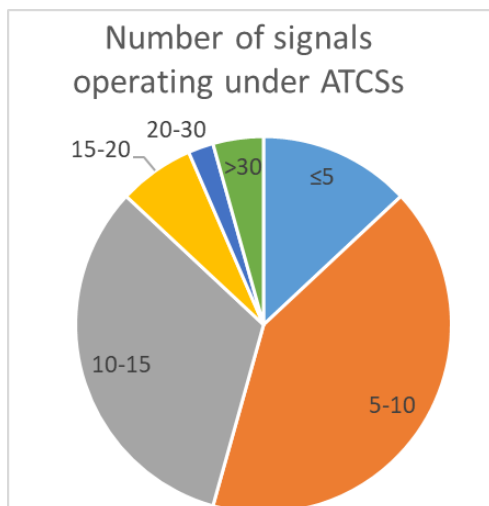
Figure E20 Distribution of ATCSs with various numbers of signals
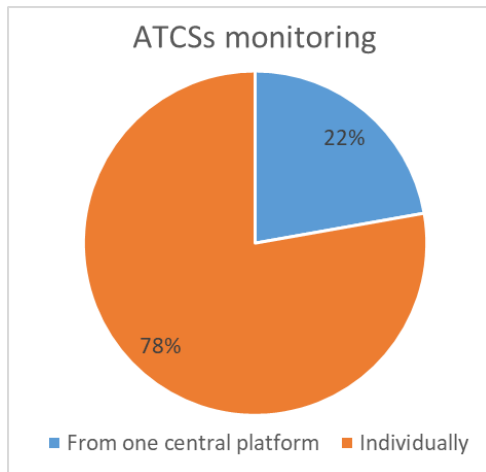
Figure E21 Proportion of ATCSs with various monitoring options

100% stacked bars are used to present AADTs (shown in Figure E22), system integration with new emerging technologies (shown in Figure E23), multimodal operations utilization (shown in Figure E24) and perception on ATCSs performance measures reduction (shown in Figure E25).
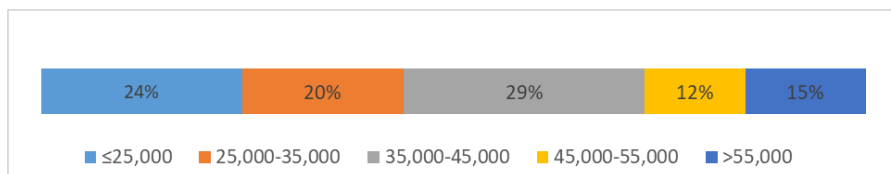
Figure E22 Distribution of ATCS deployments based on relevant AADT volumes

It needs to be mentioned that values on these charts do not always add up to 100%, because not all of the agencies provided relevant answers (thus there is sometimes a percent of blank answers).
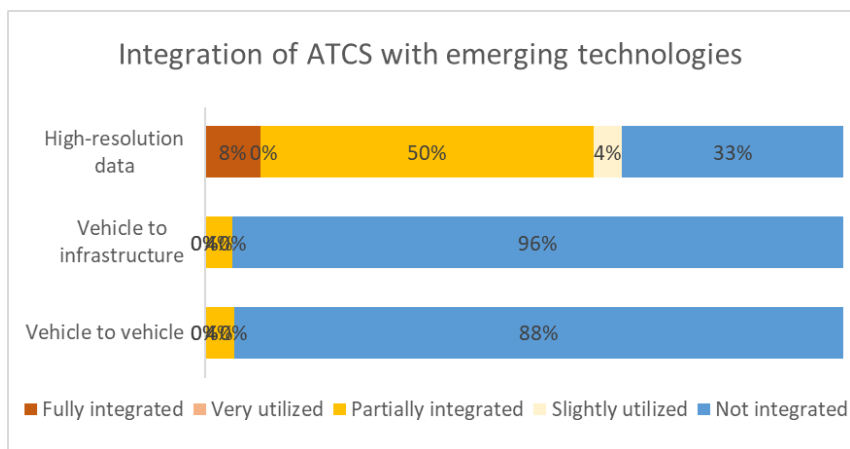
Figure E23 Percentage of ATCSs utilizing emerging technologies
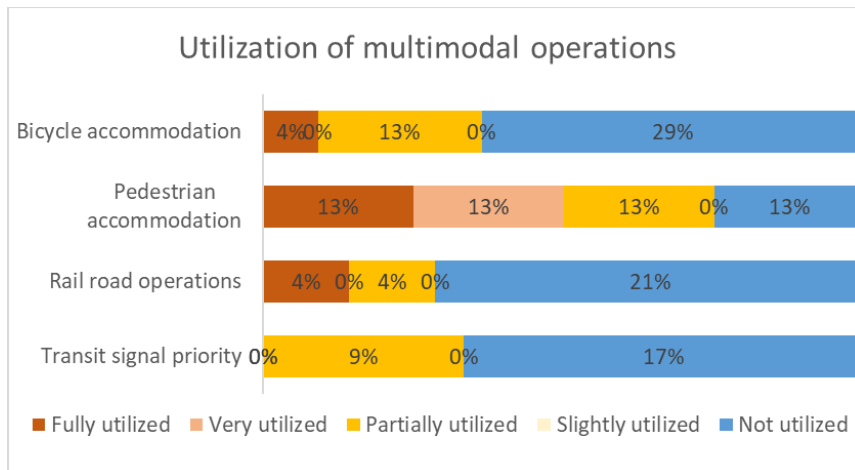
Figure E24 Percentage of ATCSs utilizing various multimodal operations
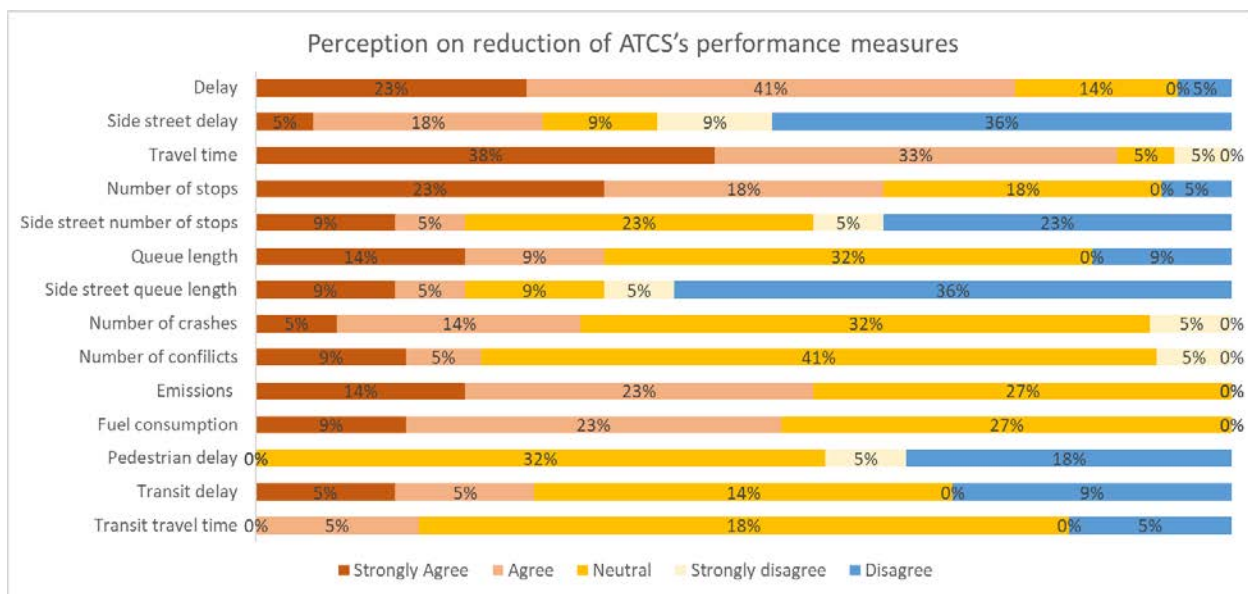
Figure E25 Perception of agencies on ATCS's improvement of performance measures

<u>Clustered column</u> charts are used to present relationship between area type and network type where particular ATCS is deployed (shown in Figure E26). The same charts are also used to show which of the signal timing parameters are adjustable in real time (shown in Figure E27).

In the cases where agencies' representatives did not report area type or network type, those answers were labeled as "Not specified".
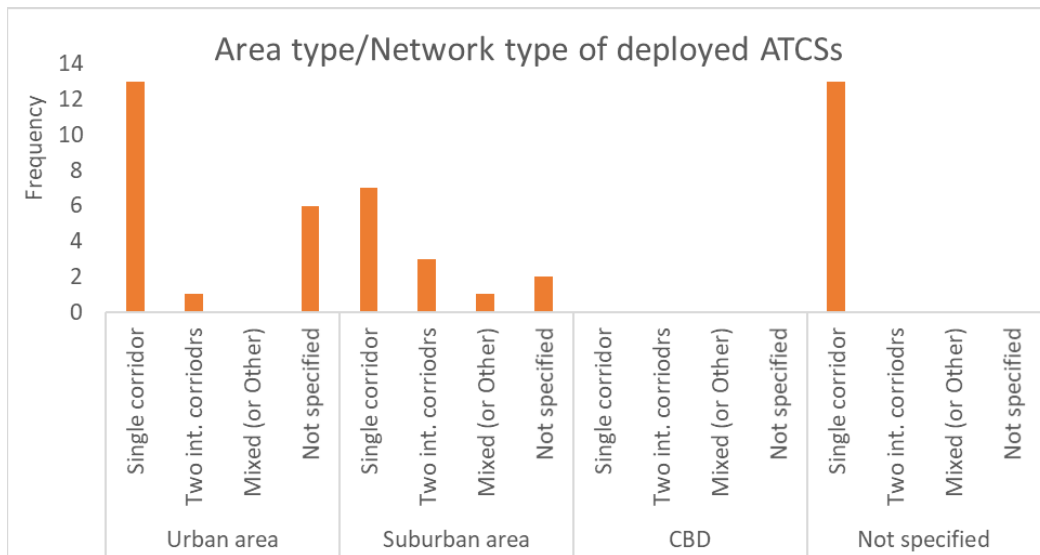
Figure E26 Distribution of deployed ATCSs per urbanized area and network type

Considering that some questions (e.g. about which signal timing parameters can be adjusted in real time) are given as "multiple answers" questions, it was beneficial to show total number of reported systems (shown under the column "Total" in Figure E27).
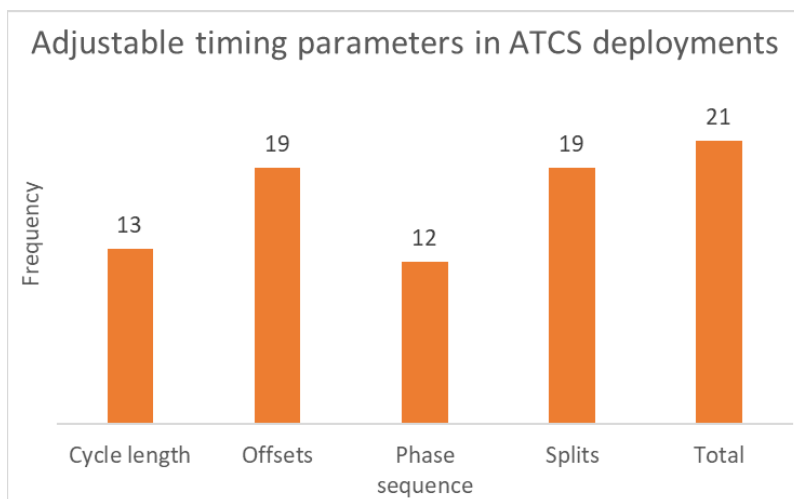
Figure E27 Frequencies of ATCSs with various signal timing options

2.3 Infrastructure & Costs

This (AT)2C dashboard page gives a user an opportunity to investigate details of the ATCSs' infrastructure and associated costs. These aspects of ATCS deployments are analyzed through various criteria's, such as, ATCSs detection technology and layout, communication infrastructure between central hardware/software and field traffic controllers, pre-ATCS signal operations and fine-tuning frequency, perception on how fundamental principles of deployed ATCS are understandable, associated costs of having such systems, and finally an expected ATCS life-span. In the case that no filtering/selection is made, the main screen of this dashboard appears as presented in Figure E28.

Figure E28 Infrastructure & costs (Dashboard Page 3)

Example: Let us consider that a user wants to filter out infrastructure data and costs for the cities and counties that have installed InSync, SCATS and SCOOT adaptive traffic control systems. Once right selections are made in the corresponding slicers, the dashboard page will look as shown in Figure E29.

Figure E29 Infrastructure & costs based on user selection

Following chart types are used to visualize results based on user selections on this dashboard page.

Pie charts are used to present pre-ATCS 'fine-tuning' frequency (as shown in Figure E30), ATCS selection method (as shown in Figure E31), and an expected ATCS lifespan (as shown in Figure E32). It

should be mentioned that for the category 'Other' of the ATCS selection method, exact responses are available in the final report of this project.
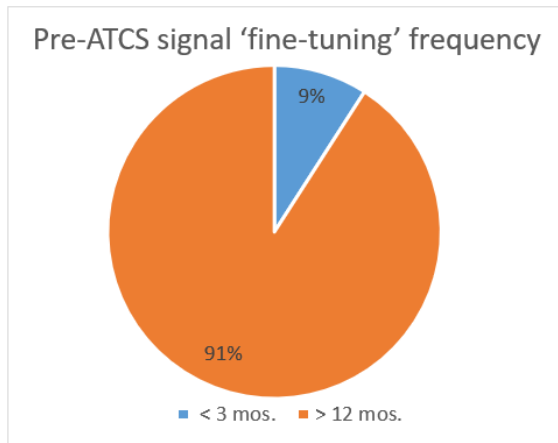
Figure E30 Frequency of pre-ATCS-deployment signal retiming
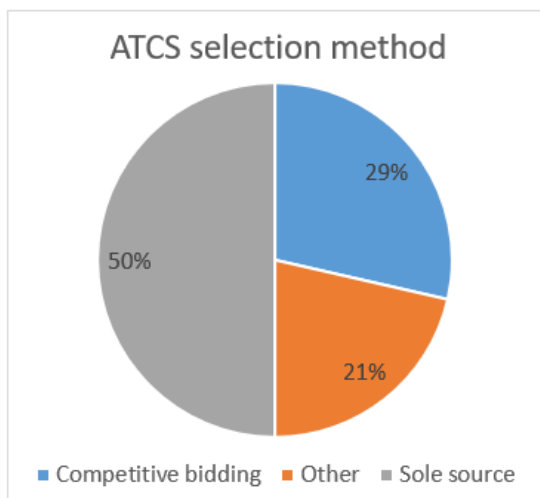
Figure E31 Distribution of methods used to select ATCS
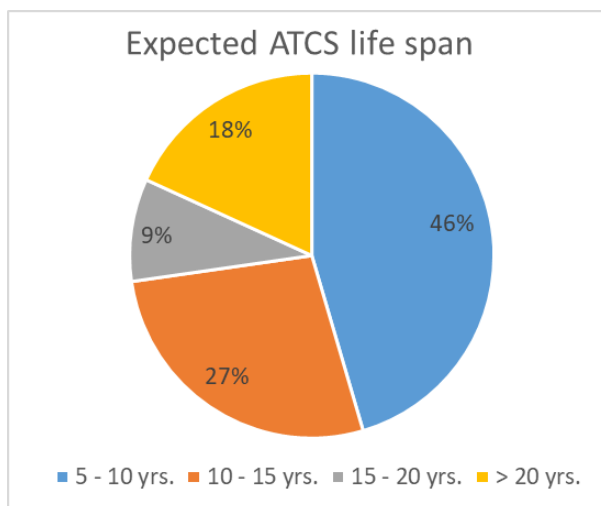
Figure E32 Expected ATCSs life span

100% stacked bars are used to present pre-ATCS signals operation (as shown in Figure E33) and to show how agency representatives perceive complexity and understandability of the fundamental principles of the deployed ATCS (as shown in Figure E34).
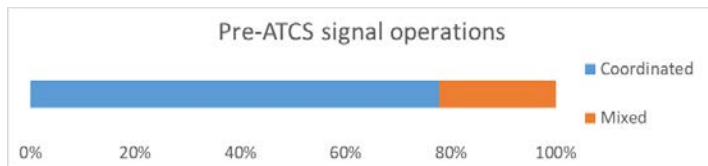
Figure E33 Distribution of pre-ATCSs signal operation modes
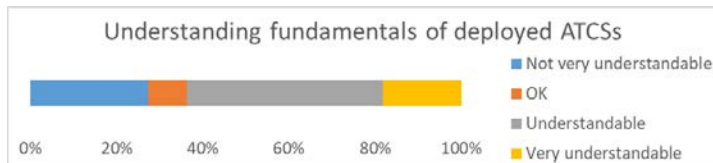
Figure E34 Distribution of perception on understanding fundamentals of deployed ATCS

Clustered bars are used to present ATCSs detection technology (as shown in Figure E35) and detection layout (as shown in Figure E36). Since each of the detection technologies/layouts is not exclusive for a single ATCS deployment (e.g. multiple detection technologies can be used for one ATCS deployment) the bar 'Total', in Figures E35 and E36, present total number of deployments when all combinations of answers with multiple detection technologies/layouts are aggregated as single entries.
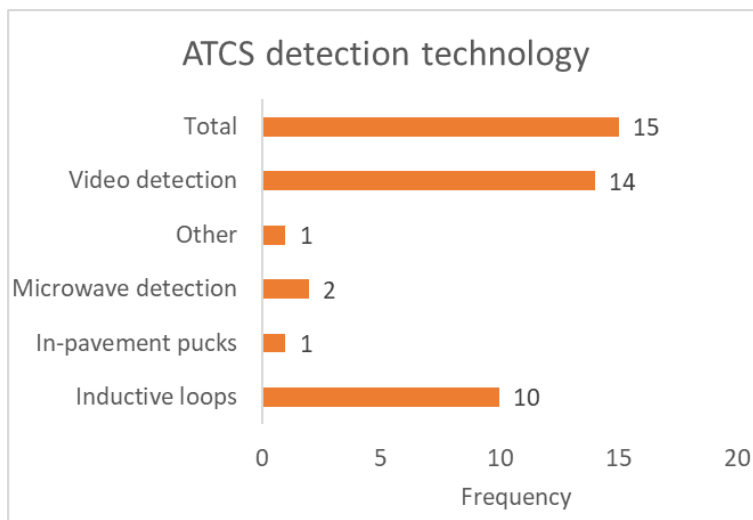
Figure E35 Frequency of various ATCS detection technologies
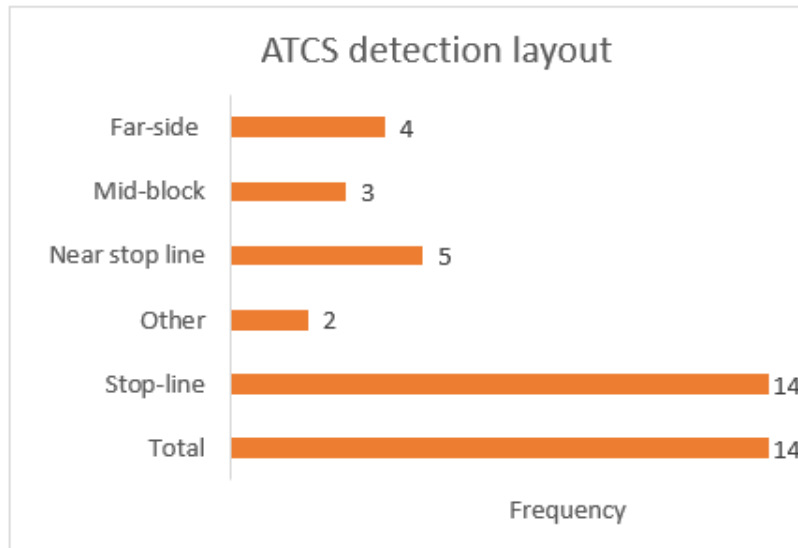
Figure E36 Frequency of various ATCS detection layouts

Clustered columns are utilized to show communication media between central hardware/software and field traffic controllers (as shown in Figure E37), as well as perception on the ATCS operation and maintenance costs (as shown in Figure E38).
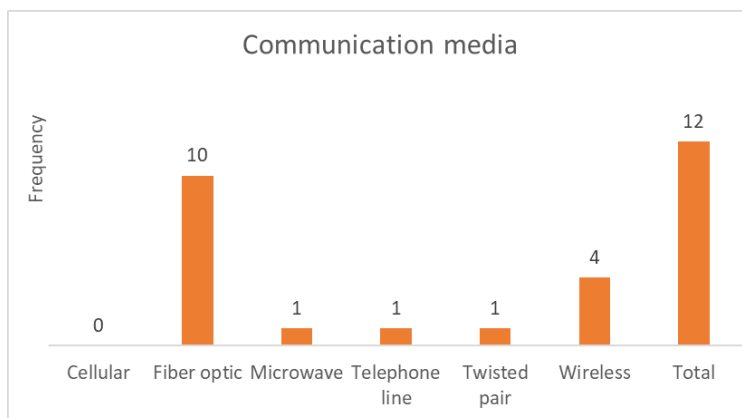
Figure E37 Frequency of communications media between ATCSs and field controllers
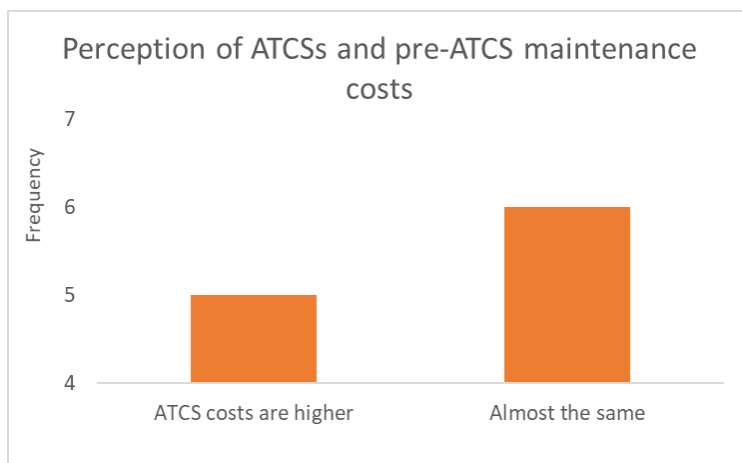
Figure E38 Perception of ATCSs and pre-ATCS-deployment maintenance costs

Box plot charts are used to illustrate: three different cost components (minimum, maximum and average) for each category, total average costs of installation per intersection, costs of installation of ATCS software, and maintenance costs of the ATCS per year (as shown in Figure E39).
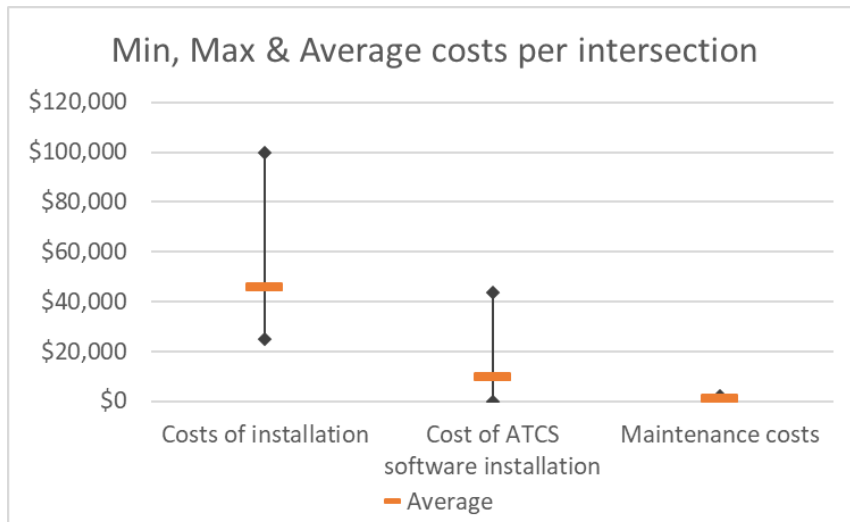
Figure E39 Min, Max & Average costs

2.4 Evaluation Details

In this dashboard page a user can use filtering and visualization tools to better understand how the evaluation(s) of deployed ATCS have been performed. Such understanding assumes having information on the three main filtering categories: evaluated ATCS brand, evaluation entity, and evaluation timeline. Visual aids are based on the main evaluation criteria's, such as, who initiated an ATCSs evaluation study, who conducted the ATCS evaluation entity, what evaluation method was used, what study types were used, and what hardware and software were instrumental for the evaluation(s). A dashboard page, with no selection made, is presented in Figure E40.
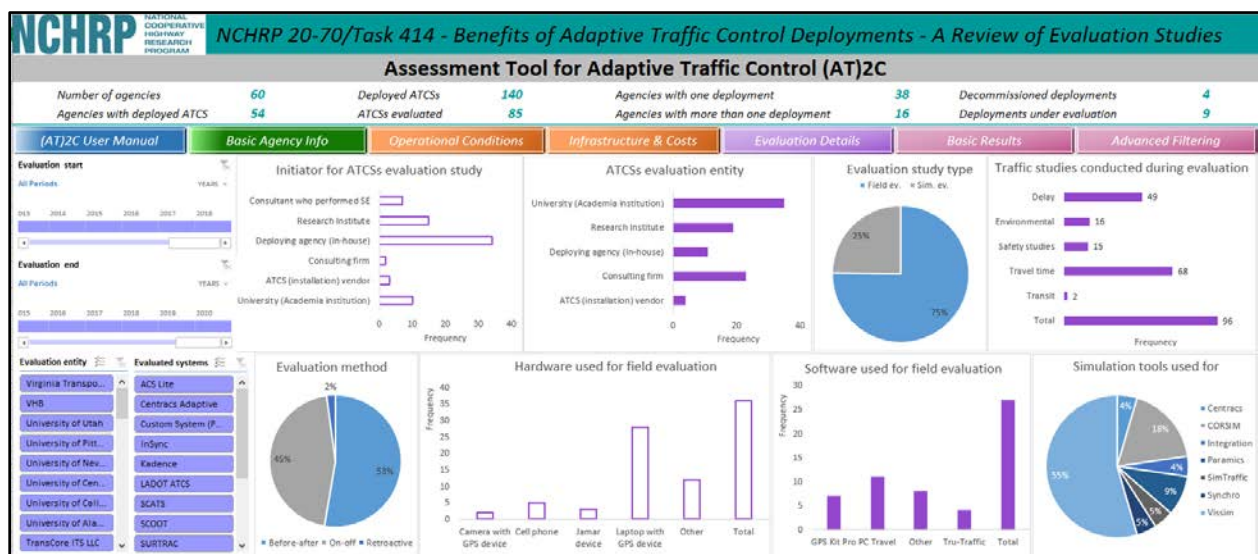
Figure E40 Evaluation details (Dashboard Page 4)

Example: Let us consider that a user wants to observe all of the data/visualization of this dashboard page (shown in Figure E41) but only for a group of the ATCS brands (e.g. ACS Lite, Centracs adaptive, InSync, Kadence, SCATS and SynchroGreen). Once he/she makes such selections in the "Evaluated ATCS" slicer, the results of the charts are updated and the resulting dashboard page looks like Figure E41.
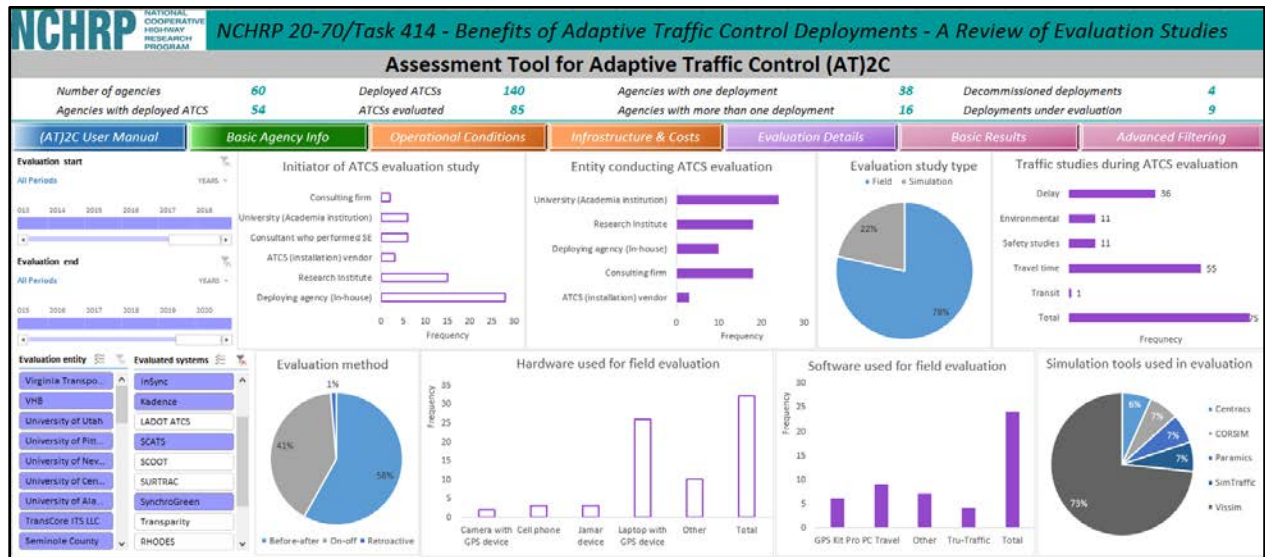

Figure E41 Evaluation details based on user selection

Following chart types are used to visualize results of the Evaluation Details dashboard.

Pie charts are used to present evaluation method (as shown in Figure E42), the type of evaluation study (as shown in Figure E43) and simulation tools used for evaluation (as shown in Figure 44).
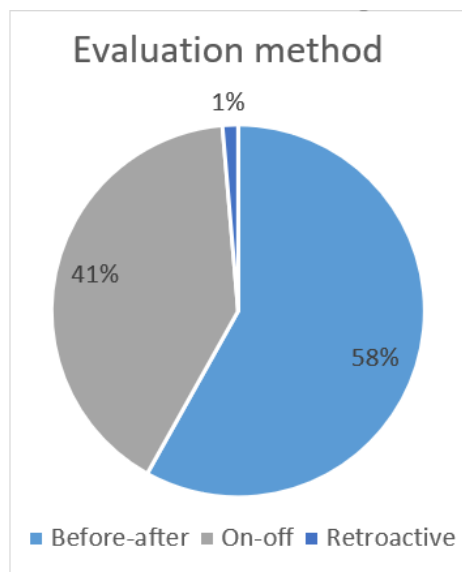
Figure E42 Evaluation method
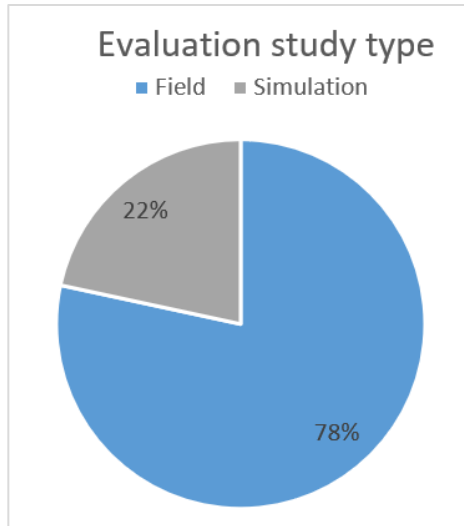
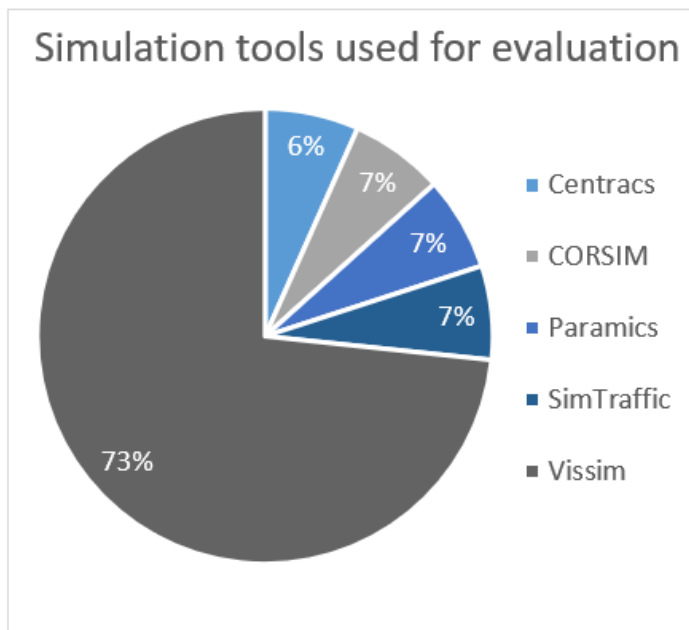**Figure E43 Evaluation study type**

Figure E44 Distribution of software simulation tools used for evaluation

Clustered bar charts are used to illustrate initiators of the ATCSs evaluation studies (as shown in Figure E45), actual ATCSs evaluation entity (as shown in Figure E46) and traffic studies conducted during evaluation of the ATCSs (as shown in Figure 47).
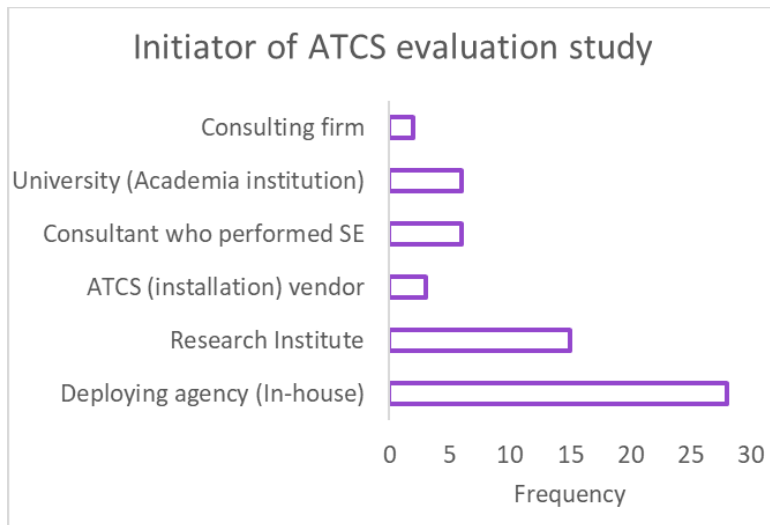
Figure E45 Distribution of initiators of the ATCSs evaluation studies
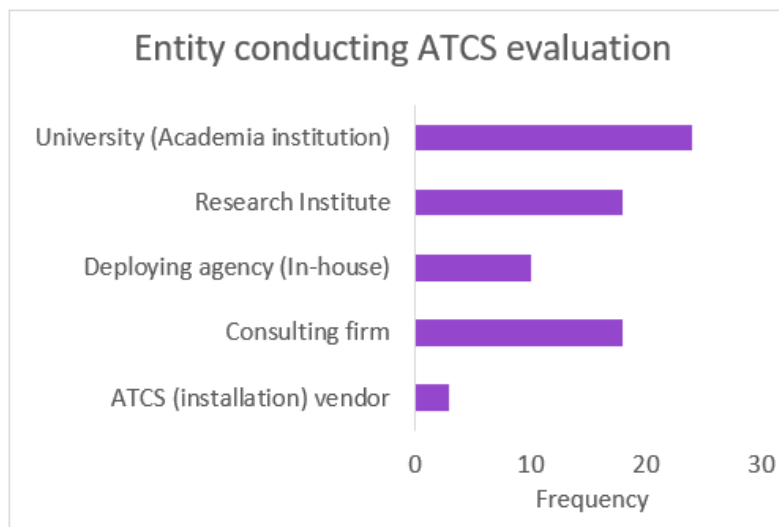

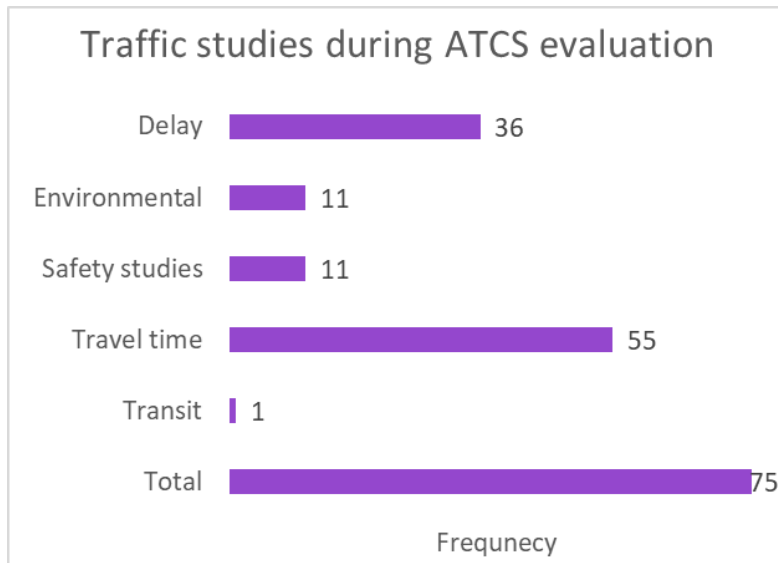**Figure E46 Distribution of initiators of the ATCSs evaluation studies**

Figure E47 Distribution of traffic studies conducted during evaluation of the ATCSs

Clustered column bar charts are used to present which hardware/software tools were used to conduct evaluation study (as shown in Figures E48 and E49). It should be mentioned that very few ATCS evaluation studies were conducted in simulation environment, so that it does not make sense to present this information visually.
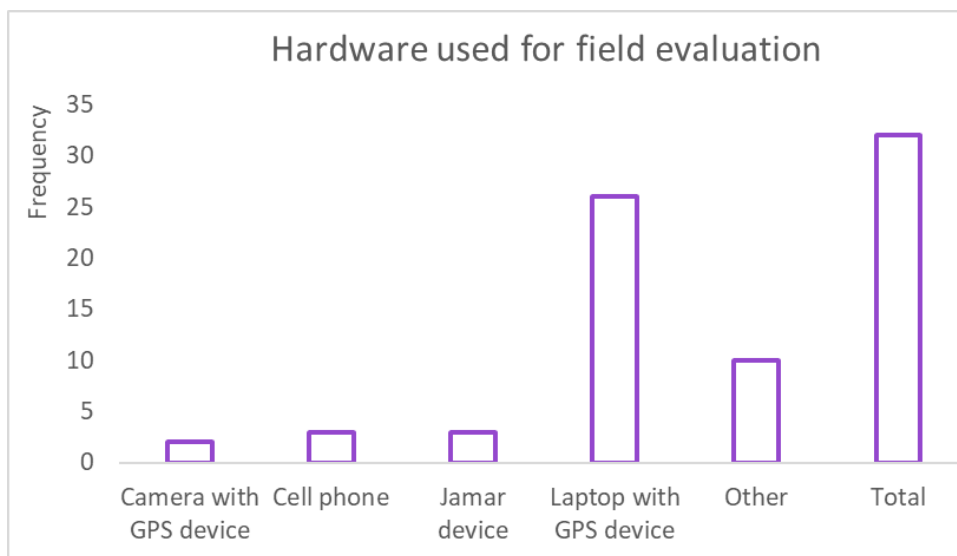

Figure E48 Frequency of data collection hardware used in evaluation studies
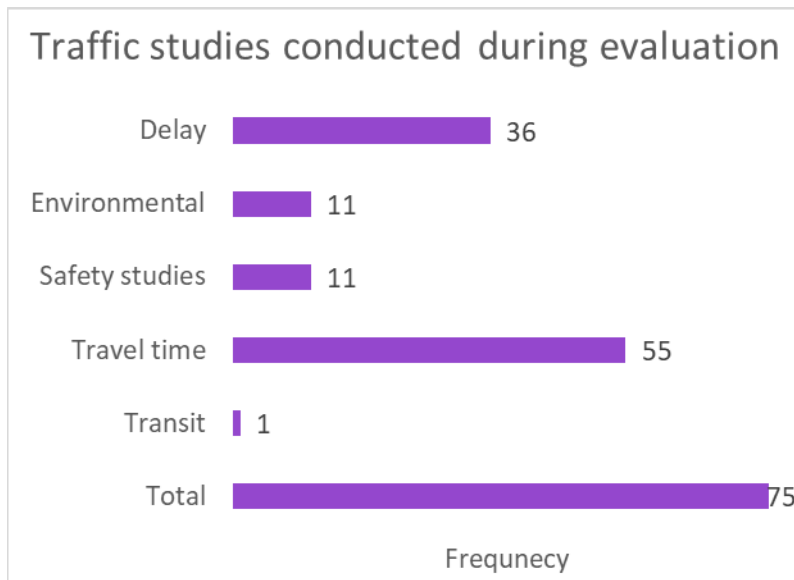
Figure E49 Frequency of software used in evaluation studies

3. (AT)2C – Filtering Tool

Another feature of the (AT)2C tool is ability to filter evaluation results (e.g. delays, travel times and similar). This capability allows user to run analyses based on less (Basic Results) or more (Advanced Filtering) customized ways (by filtering various criteria's). As an output, a user gets a chance to observe benefits of various performance measures reported for different time periods (e.g. TODs) in the evaluation studies. Moreover, for each performance measure benefit, a user can observe which record number in the database corresponds to a particular evaluation. This record number can be used, later, to identify by which agency, system was installed, evaluated and similar.

3.1 Basic Results

Within this (AT)2C section a user can investigate benefits of deploying a particular system. Unlike an advanced filtering page, which will be discussed later, such investigation is done with the most basic filtering options and visualization aids. The main screen of this dashboard is presented in Figure E50.
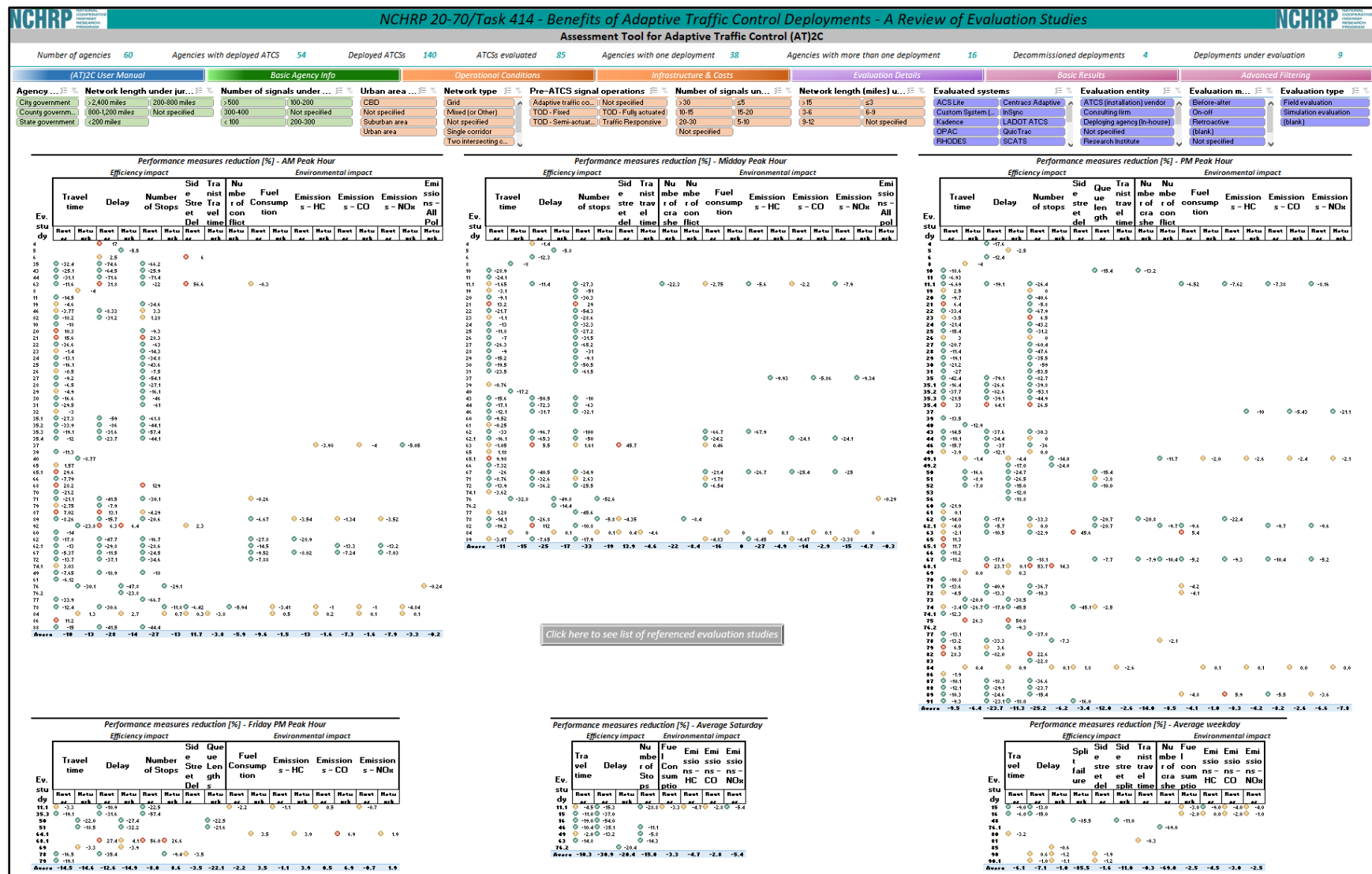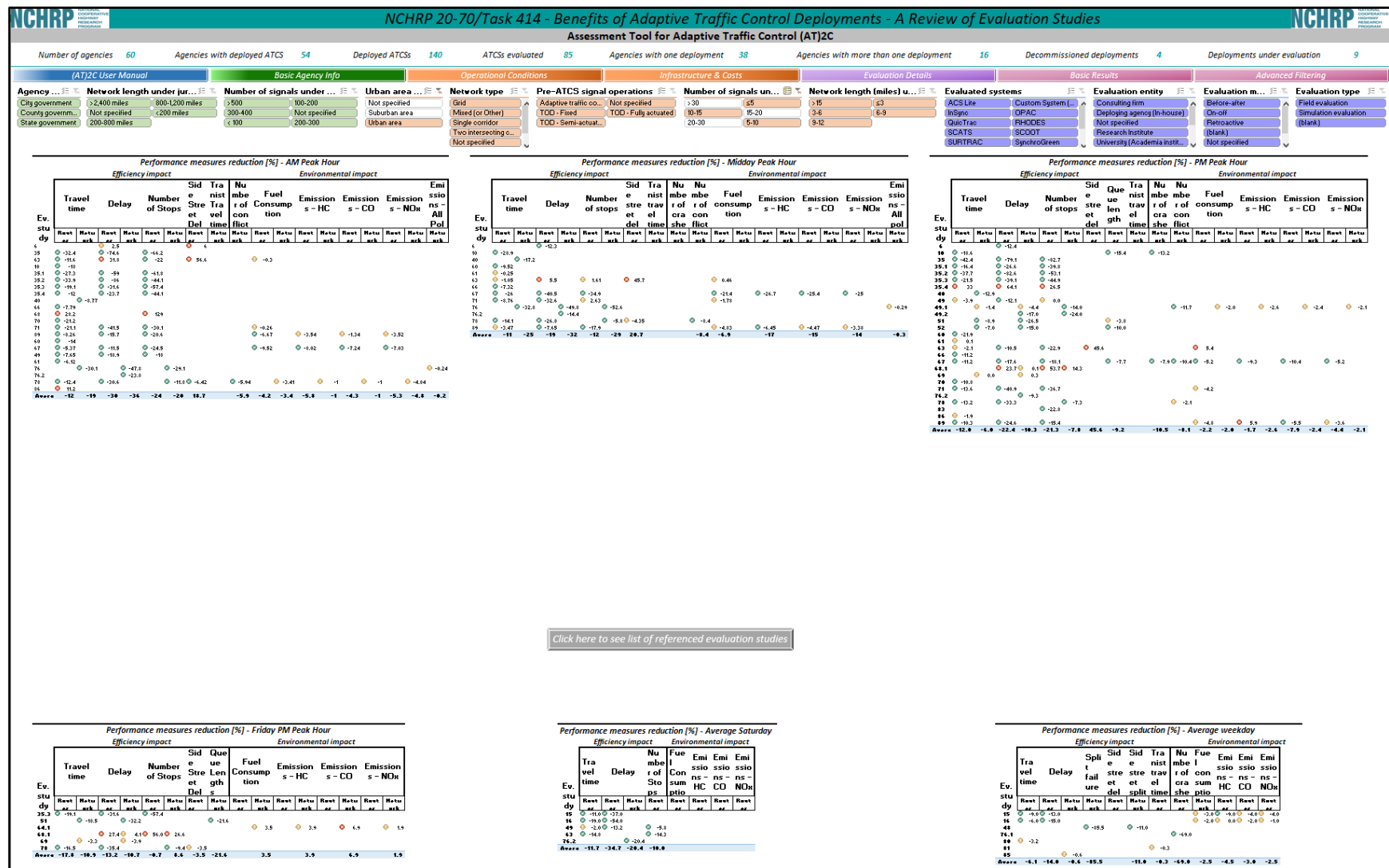
Figure E49 Basic results

__Example:__ Let us consider a case where a user wants to investigate ATCS benefits from for all of the evaluations with up to 15 traffic signals, where such ATCSs are deployed in urban areas. Based on these criteria, resulting performance measure benefits are shown in tabular forms as depicted by Figure E50.

Once this selection is made, a user can observe benefits which are reported in the evaluation studies. Further, to enable a user to connect such results with the underlying evaluation studies, a user is given a chance click on the button "*Click here to see a list of referenced evaluation studies*" to see the relevant studies. The list of referenced evaluation studies basically contains only those studies that result from filtering process (as shown in Figure E51). By following a particular record number, a user can observe which particular agency conducted a particular evaluation study. In order to return to previous dashboard page (i.e., Basic Results), a user is given a chance to click on the button "Go back to Basic Results" (as shown in Figure E51).

Figure E50 Basic results based on user selection

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| List of referenced studies | Go back to Basic Results |

California Department of Transportation - Sacramento
40. Skabardonis, A. and Gomes, G., 2010. Effectiveness of Adaptive Traffic Control for Arterial Signal Management: Modeling Results.

City of Atlanta
70. Wang, J., Robinson, B., Shelby, S.G., Cox, K.B. and Townsend, W., 2010. Evaluation of ACS lite adaptive control using Sensys Arterial Travel Time data. In ITS America 20th Annual Meeting & ExpositionITS America.

City of Austin
18. Not evaluated

City of Boca Raton
80. So, J., Stevanovic, A., Posadas, E. and Awwad, R., 2014. Field Evaluation of a SynchroGreen Adaptive Signal System. In 2nd American Society of Civil Engineers (ASCE) Transportation and Development Institute (T&DI) Conference Proceedings.

City of Chula Vista
89. Chau C., and Al-Aga, S., 2003. Adaptive traffic control system using SCATS. Land development and Transportation Divison Engineering Department, City of Chula Vista, California.

City of Harrisburg
57. Not evaluated

City of Madison Traffic Engineering
42. Not provided

City of Philadelphia
34. Not provided

City of Pittsburgh
76. Smith, S.F., Barlow, G.J., Xie, X.F. and Rubinstein, Z.B., 2013, June. Smart urban signal networks: Initial application of the surtrac adaptive traffic signal control system. In Twenty-Third International Conference on Automated Planning and Scheduling.
76.1. khattak, Z.H., Magalotti, M.J. and Fontaine, M.D., 2018. Estimating safety effects of adaptive signal control technology using the Empirical Bayes method. Journal of safety research, 64, pp.121-128.
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City of Port St. Lucie
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35.1. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report
35.2. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report
35.3. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report
35.4. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report

City of Portland
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b) Figliozzi, Miguel A., and Christopher Monsere. "Evaluation of the Performance of the Sydney Coordinated Adaptive Traffic System (SCATS) on Powell Boulevard in Portland, OR." OTREC -RR-13-07. Portland, OR: Transportation Research and Education Center (TREC) 2013.
c) Slavin, C., Feng, W., Figliozzi, M. and Koonce, P., 2013. Statistical study of the impact of adaptive traffic signal control on traffic and transit performance. Transportation Research Record, 2356(1), pp.117-126.

City of Renton
17. Not evaluated

Cobb County
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Collier County
54. Not provided

Colorado Department of Transportation - Greeley
15. Sprague, D., 2012. Adaptive Signal Timing Comparison Between the InSync and QuicTrac Adaptive Signal Systems Installed in Colorado (No. CDOT-2012-6). Colorado. DTD Applied Research and Innovation Branch.

Colorado Department of Transportation - Woodland Park
16. Sprague, D., 2012. Adaptive Signal Timing Comparison Between the InSync and QuicTrac Adaptive Signal Systems Installed in Colorado (No. CDOT-2012-6). Colorado. DTD Applied Research and Innovation Branch.

Maryland DOT State Highway Administration - Hanover
2. Not evaluated
6. In house evaluation

Missouri Department of Transportation - Kansas
10. Hutton, J.N., Bokenkroger, C.D. and Meyer, M.M., 2010. Evaluation of an adaptive traffic signal system: route 291 in Lee's Summit, Missouri (No. OR 10-020).

Nevada Department of Transportation - Las Vegas
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New Jersey Department of Transportation - New Brunswick
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New York State Department of Transportation - Albany
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New York State Department of Transportation - White Plains
64. Lardoux, J., Martinez, R., White, C., Gross, N., Patel, N. and Meyer, R., 2014. Adaptive Traffic Signal Control for Tarrytown Road in White Plains, New York (No. C-10-17).
64.1. Ban, X. and Sun, Z., 2013. Simulation-based decision-making tool for adaptive traffic signal control on Tarrytown Road in the City of White Plains (No. C-10-03). New York State Energy Research and Development Authority.

Oregon Department of Transportation - Salem
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Palm Beach County
60. Jeedigunta, G., 2017. Moving Traffic using Adaptive Traffic Control System, Okeechobee Blvd. and Northlake Blvd. evaluation study. Palm Beach County, Florida.
61. Jeedigunta, G., 2017. Moving Traffic using Adaptive Traffic Control System, Okeechobee Blvd. and Northlake Blvd. evaluation study. Palm Beach County, Florida.

Pinellas County
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Seminole County
67. Cheek, M., Wetzel, C. and Dickson, C., 2012. SynchroGreen Real-Time Adaptive Traffic Control System Seminole County Deployment. In ITE 2012 Annual Meeting & ExhibitInstitute of Transportation Engineers (ITE).

Utah Department of Transportation - Salt Lake City
48. Richardson, L.M., Luker, M.D., Day, C.M., Taylor, M. and Bullock, D.M., 2017. Outcome Assessment of Peer-to-Peer Adaptive Control Adjacent to a National Park. Transportation Research Record, 2620(1), pp.43-53.
49. Martin, P.T. and Stevanovic, A., 2008. Adaptive Signal Control V-SCATS Evaluation in Park City, Utah (No. MPC Report No. 08-200).
49.1. a) Stevanovic, A., Stevanovic, J. and Kergaye, C., 2012, January. Environmental benefits of adaptive traffic control system: Assessment of fuel consumption and vehicular emissions. In 91st Annual Meeting of the Transportation Research Board, Washington, DC.
b) Stevanovic, A., Kergaye, C. and Haigwood, J., 2011, September. Assessment of surrogate safety benefits of an adaptive traffic control system. In 3rd International Conference on Road Safety and Simulation, Indianapolis, IN.
49.2. Stevanovic, A., Kergaye, C. and Stevanovic, J., 2012. Long-term benefits of adaptive traffic control under varying traffic flows during weekday peak hours. Transportation Research Record, 2311(1), pp.99-107.
51. a) Martin, P.T., Perrin, J., Chilukuri, B.R., Jhaveri, C. and Feng, Y., 2003. Adaptive signal control II (No. UT-03.28, UTL-0902-60). University of Utah. Dept. of Civil and Environmental Engineering.
52. a) Martin, P.T., Perrin, J., Chilukuri, B.R., Jhaveri, C. and Feng, Y., 2003. Adaptive signal control II (No. UT-03.28, UTL-0902-60). University of Utah. Dept. of Civil and Environmental Engineering.
b) Jhaveri, C.S., Perrin, J. and Martin, P., 2003, January. SCOOT adaptive signal control: An evaluation of its effectiveness over a range of congestion intensities. In Transportation Research

Volusia County
78. a) Stevanovic, A. and Zlatkovic, M., 2013. Evaluation of InSync adaptive traffic signal control in microsimulation environment(No. 13-0487).
b) Stevanovic, A., Dakic, I. and Zlatkovic, M., 2016. Comparison of adaptive traffic control benefits for recurring and non-recurring traffic conditions. IET Intelligent Transport Systems, 11(3), pp.142-151.

Wakefield Public Works Department
41. Not provided

Figure E51 List of database items

3.2 Advanced Filtering

Under "Advanced Filtering", a user can obtain the same type of results as in the "Basic Results" section but he/she has ability to apply numerous filtering categories. The main screen of this section is presented in Figure E52. The procedure explained in section 3.1 of this manual applies as well for the "Advanced filtering".

Example: Let us consider that a user wants to find out what are the benefits of evaluated ACS Lite, InSync, OPAC, Kadence, by city agency, on single corridor, that belongs to metropolitan areas, when evaluation is performed by consulting firm, in the time span of 2013 – 2020. Once he/she makes such selections in the appropriate slicers, the performance reduction tables are updated and the resulting dashboard page looks like Figure E53.

It can be seen that for several chosen criteria's, which covers major groups identified for each deployment /evaluation (i.e., basic agency info, operational conditions and evaluation details) five evaluation studies were listed fulfilling all criteria's defined by user. It needs to be stated that performance measures which are derived by considering only traffic conditions based on several vehicle trajectories on during evaluation are presented as "Routes based" while if the performance measures were obtained considering trajectories of all vehicles (usually obtainable in simulation evaluation) are presented in "Network level" columns of pivot tables presented within this dashboard section.

Once this selection is made, a user can observe benefits which are reported in the evaluation studies. Further, to enable a user to connect such results with the underlying evaluation studies, a user is given a chance click on the button "*Click here to see a list of referenced evaluation studies*" to see the relevant studies. The list of referenced evaluation studies basically contains only those studies that result from filtering process (as shown in Figure E54). By following a particular record number, a user can observe which particular agency conducted a particular evaluation study. In order to return to previous dashboard page (i.e., Advanced Filtering), a user is given a chance to click on the button "Go back to Advanced Filtering" (as shown in Figure E54).
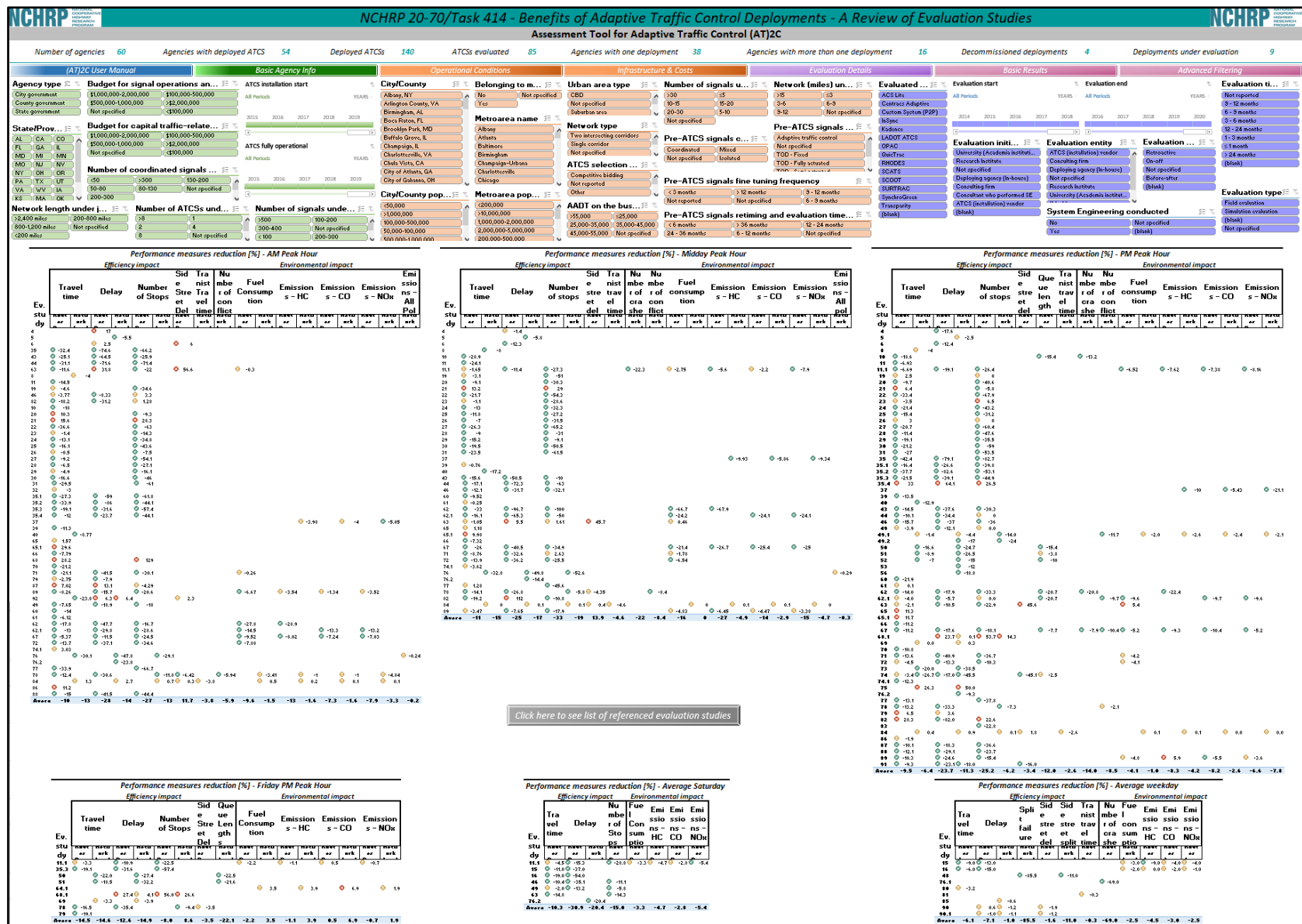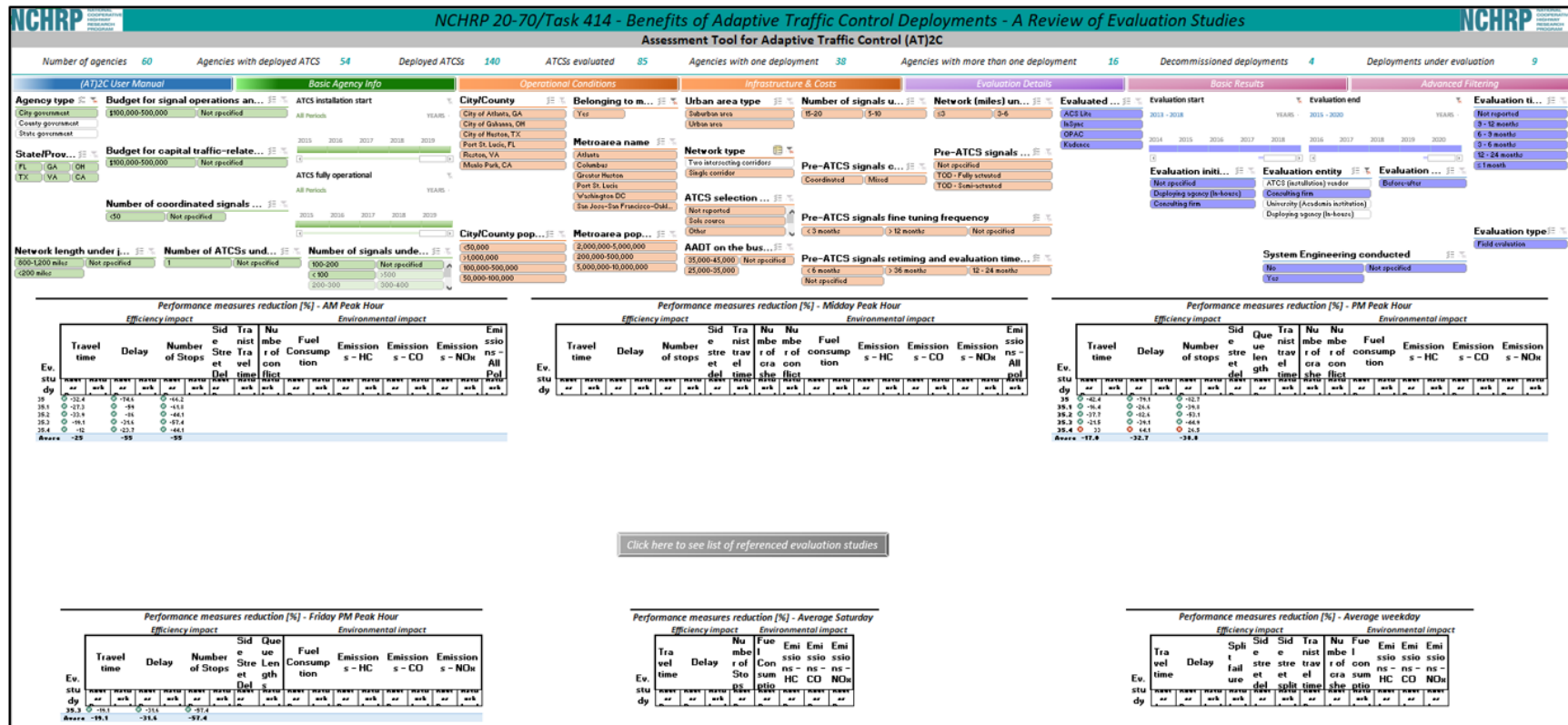
Figure E52 Advanced filtering

Figure E53 Advanced filtering based on user selection

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List of referenced studies

Go back to Advanced Filtering

City of Port St. Lucie

35. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report

35.1. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report

35.2. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report

35.3. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report

35.4. Marlin Engineering, Inc., 2019. Travel Time and Delay Study – St. Lucie West Boulevard - Interstate 95 northbound off/on-ramp terminal intersection to NW/SW Bayshore Boulevard, Phase III, Draft Report

Figure E54 List of database items