EVALUATING AND VISUALIZING MULTIMODAL NETWORKS AT SCALE

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ABSTRACT

Improvements in technology, performance metrics and the increased availability of big data are re-shaping the transportation planning industry and catalyzing change in the way planners and engineers evaluate transportation systems. The Alameda Countywide Multimodal Arterial Plan (MAP) is a recently completed planning effort that evaluated a 1,200-mile arterial system using geographic information system (GIS) technology, big data and various performance metrics. The creation of an automated GIS cross-sectional evaluation tool (GIS Tool) and visualization framework intended to enable large scale scenario planning efforts for multimodal transportation system analysis was a key development of the MAP. This GIS Tool has the capability to evaluate multimodal performance, identify multimodal network needs and recommend infrastructure improvements for implementation within available right-of-way to address network needs. The GIS Tool also automates the creation of three-dimensional (3D) renderings to visualize cross-sectional improvements at scales not previously feasible. As a result of these innovations, a set of recommended multimodal network improvements were identified at large scale to inform decision makers within Alameda County on infrastructure improvements that can increase the arterial system throughput by creating continuous and connected multimodal networks and expanding the number of people served via all modes. This paper presents the methodology and approach for developing the GIS Tool – including potential applications – to provide a framework for public agencies to utilize the latest innovations in technology, big data and performance metrics, and guide investments in transportation infrastructure.

Keywords: Arterial, Multimodal, Cross-Section, Procedural Modeling, GIS, Big Data

INTRODUCTION

Alameda County, located at the center of the San Francisco Bay Area region, has experienced an increase in freeway and arterial congestion every year since 2010 (*1*). Congestion, measured as a function of travel speed, is expected to worsen with the anticipated growth in jobs, housing and population throughout the region coupled with the reality that increasing automobile capacity via roadway widening is becoming less feasible (*2*). Arterials are a critical component of the countywide transportation system: they connect communities to the regional transportation network while having a local function, context and character. Arterials carry about 40 percent of average daily traffic (ADT) volumes in Alameda County (*3*) and serve a wide range of land uses and travel modes, including transit, pedestrians, bicyclists, automobiles and goods movement.

Alameda County's arterials are the only major roads that serve all modes, thus providing the greatest opportunity to increase person throughput by creating continuous and connected networks for all roadway users. For this reason, the Alameda County Transportation Commission (Alameda CTC) led the development of the Alameda Countywide Multimodal Arterial Plan (MAP) in an effort to improve mobility for all modes across the county. The MAP attempted to identify multimodal infrastructure improvements that would provide a set of efficient, safe and equitably accessible arterials that facilitate the multimodal movement of people and goods. To achieve the MAP's vision, it was critical for Alameda CTC and stakeholders throughout the county to consider innovative approaches to manage the transportation network (*4*).

The MAP project team developed a powerful automated cross-sectional evaluation tool and database, referred to as the GIS Tool, to measure the performance of each mode, how much right-of-way (ROW) may be available on each study segment to repurpose for other modes, and the improvements that would help these segments meet the performance objectives for priority modes. This unprecedented GIS Tool made it possible to perform a large-scale cross-sectional evaluation of the countywide arterial system while automating the development of 3D street renderings to visualize recommended multimodal infrastructure improvements. This analysis framework provides a model example for public agencies to utilize the latest innovations in technology, big data and performance metrics to inform investments in transportation infrastructure.

This paper concludes with challenges encountered while developing the GIS Tool, and potential ways the tool can be improved for future uses.

LITERATURE REVIEW

Many public agencies are challenged to apply robust, data-driven analyses to identify multimodal network needs and improvements. The Alameda Countywide Multimodal Arterial Plan study created a ground-breaking GIS Tool to identify multimodal network improvements that provide the basis for project development. This analysis framework can be applied in any city, county or state. Although there is no existing precedent for the GIS Tool, various resources were reviewed to help guide the tool's development.

Right-of-Way Reallocation and Roadway Design

The National Association of City Transportation Officials (NACTO) has developed various roadway design guidelines emphasizing the concept of flexibility in design, including guides for the development of bikeways, urban streets and transit streets (*5*, *6*, *7*). The minimum widths of typical cross-sectional elements (e.g., parking lanes, bike lanes, travel lanes, medians) recommended in the NACTO design guidelines served as the basis in the GIS tool for determining available ROW within the existing curb-to-curb width. Existing cross-sectional measurements were compared to the minimum recommended widths for specific cross-sectional elements and the difference in width was considered to be the available ROW that could be repurposed for specific improvements by mode. The GIS Tool also incorporates the ability to recommend specific improvements by mode that can fit within the available ROW using the NACTO design guidelines as reference.

The open source Streetmix website also provided the inspiration to effectively visualize the reconfiguration of cross-sectional elements at large scales (*8*).

Performance Measures and Objectives

The MAP moved beyond vehicle Level of Service (LOS) by utilizing various performance measures to assess the multimodal functions for all modes on each arterial segment. Performance measures were a critical element of the GIS Tool functionally, which allows the large-scale evaluation of multimodal performance. The application of various performance measures to better evaluate multimodal system performance is consistent with the Smart Mobility Framework developed by California Department of Transportation (*9*). The following are the primary performance measures utilized as part of the MAP and incorporated into the GIS Tool:

- Transit Travel Speed during the PM peak hour was evaluated based on data obtained from on-board global positioning system (GPS) tracking devices.
- Transit Reliability, considered the ratio of PM peak hour travel speed to non-peak hour speed based on data obtained from on-board GPS tracking devices.
- Transit Infrastructure Index is an assessment of typical bus stop design along an arterial segment and the measure is based on similar performance measure applied in the Ashland-Cherryland Business District Specific Plan in unincorporated Alameda County (*10*).
- Pedestrian Comfort Index is an assessment of pedestrian infrastructure based on sidewalk width, presence of buffer, typical crossing distance, roadway volumes and speed. This performance measure methodology parallels the Mineta Transportation Institute's Level of Traffic Stress framework (*11*).
- Bicycle Comfort Index is an assessment based on the Mineta Transportation Institute's Level of Traffic Stress methodology (*12*).
- Automobile Congested Speed during the PM peak period, consistent with the methodology utilized by the Alameda CTC Congestion Management Program (*13*).
- Volume-to-Capacity Ratio during the PM peak hour, similar to the methodology in the 1994 Highway Capacity Manual (*14*).
- Truck Route Accommodation Index is an assessment of curb lane width, a measure unique to this study.

Performance objectives, or thresholds, to identify which segments need improvements were established for each of the eight performance measures listed above based on extensive collaboration with staff from all 14 cities in Alameda County, Alameda County staff and local transit agency staff (*4*).

Procedural Modeling

While there are various procedural modeling applications, this paper focuses on the rules based modeling program CityEngine. CityEngine is a procedural modeling software designed to efficiently generate 3D city models including roadways and adjacent land uses (*15*). The software was originally developed for the motion picture industry; however, it has started to be incorporated into urban planning applications because of its ability to efficiently generate high quality 3D models at large scales (*15*, *16*). The basic idea behind CityEngine is the use of initial start shapes and a programming language called Computer Generated Architecture (CGA) to transform attributes in GIS databases into progressively more complex procedural 3D models (*17*). While typical applications of CityEngine have focused on communicating different land use scenarios or visualizing comprehensive plans (*15*, *16*), the software also has the ability to create procedural streets based on typical cross-section measurement data. The application of procedural modeling in this study focuses solely on its promise to enable planners to represent streets and proposed improvements at scales and quantities not previously feasible (*15*, *17*).

METHODOLOGY

The MAP technical analysis framework consisted of the following primary tasks (**Figure 1**):

- Data collection – the gathering of readily-available data.
- Database development – the platform to effectively manage data.
- GIS Tool development – the series of scripts developed to perform the multimodal evaluation.
- Project team review – the review of databases, GIS Tool scripts and analysis results by project team staff for quality assurance and quality control.
- Improvement recommendations – the development of multimodal infrastructure improvement recommendations.
- Jurisdiction review – the project team collaborated extensively with the owners and operators of arterials to review the analysis framework assumptions and improvement recommendations.

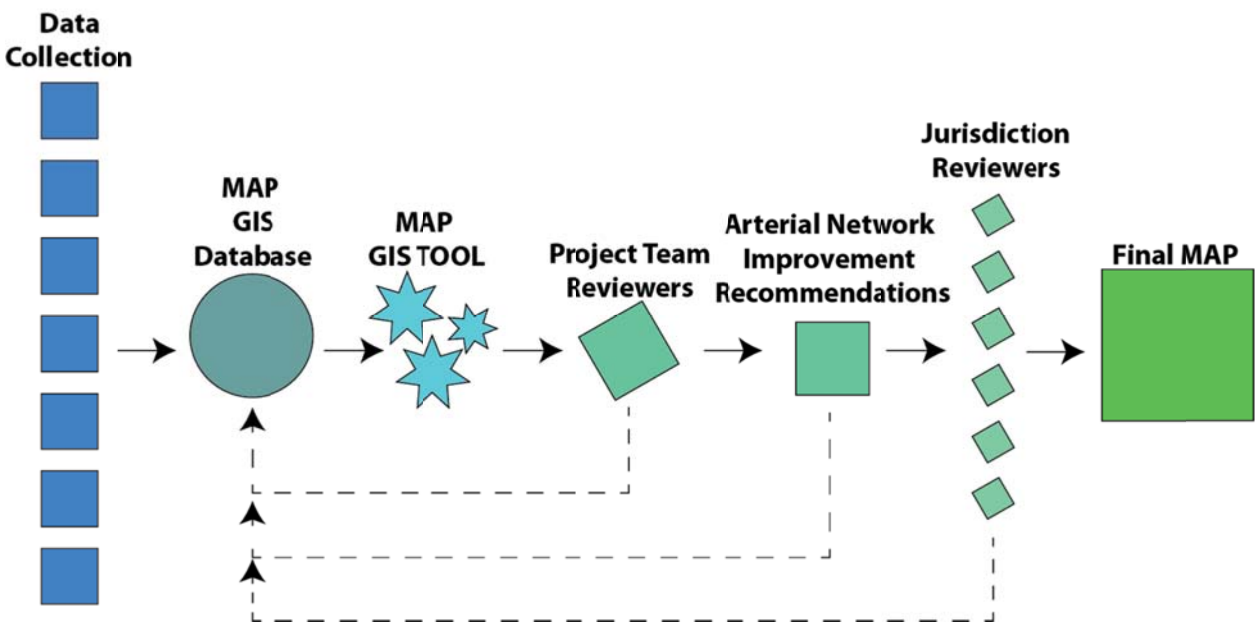

FIGURE 1 GIS Tool and Improvement Recommendation Process Diagram.

Data Collection

The MAP evaluated a 1,200-mile roadway network consisting of arterials and collectors compliant with the California Road System (CRS) classification. This countywide roadway system, known as the Study Network, was evaluated to understand existing and future year roadway operating conditions for all five major travel modes: auto, transit, bike, pedestrian, and goods movement. A large data collection effort was undertaken to gather readily-available data to inventory existing multimodal infrastructure and travel demand to provide the necessary inputs for evaluating multimodal performance measures and develop a baseline for estimating future year travel demand. The information collected for each study segment (**Table 1**) was detailed enough that it enabled planners to translate various attributes in the database into cross-sectional visualizations that could be altered based on a subset of attributes.

The existing infrastructure, roadway performance and demand and land use data generally covered 20 to 100 percent of the Study Network (240 to 1,200 miles). The extent of data coverage varies by type of data and source. For example, cross-sectional data was limited to the amount of data that could be collected within the project budget and schedule. Although data was not collected for the full 1,200-mile Study Network, the multimodal evaluation for this study focused primarily on a subset network representing arterials of countywide significance, which consisted of 510 miles of roadway as identified via extensive stakeholder collaboration, known as the Arterial Network (**Figure 2**).

TABLE 1 MAP Data Collection Summary

List of Data	Data Description	Data Source	Data Coverage (miles)
Cross-sectional measurements and design characteristics	Cross-sectional measurements include: ▪ Sidewalk width ▪ Sidewalk buffer width and type ▪ Parking lane width and control type ▪ Bicycle lane width ▪ Bicycle lane buffer width ▪ Presence of bicycle sharrow ▪ Travel lane width ▪ Median width and type ▪ Posted speed limit ▪ Curb and curb extension presence ▪ Typical bus stop amenities ▪ Presence of curb extension ▪ Typical crosswalk control	Aerial imagery and design files provided by local jurisdictions	670
Automobile volumes	Average daily traffic (ADT) volumes & PM peak hour counts, including truck percentages	Alameda CTC Travel Demand Model, and count data provided by local jurisdictions	980
Automobile travel speed	Average PM peak period automobile speeds	INRIX, Alameda CTC Travel Demand Model, and speed data provided by local jurisdictions	980
Transit speed	PM peak hour transit speed	Local transit agencies	240
Transit reliability	PM peak hour transit Reliability	Local transit agencies	240
Transit routes	Study Network segments that serve fixed-transit routes	Local transit agencies	480
Pavement condition index (PCI)	PCI rating	MTC Streetsaver Database	960
ITS infrastructure	Inventory of the level of ITS infrastructure that exists or is planned and funded	Local jurisdictions	390
Goods movement routes	Countywide goods movements routes	Local jurisdictions and Alameda CTC	670
Land Use	Countywide land use data aggregated at the TAZ level	Association of Bay Area Governments (ABAG), Sustainable Communities Strategy Land Use, local jurisdictions	1,200

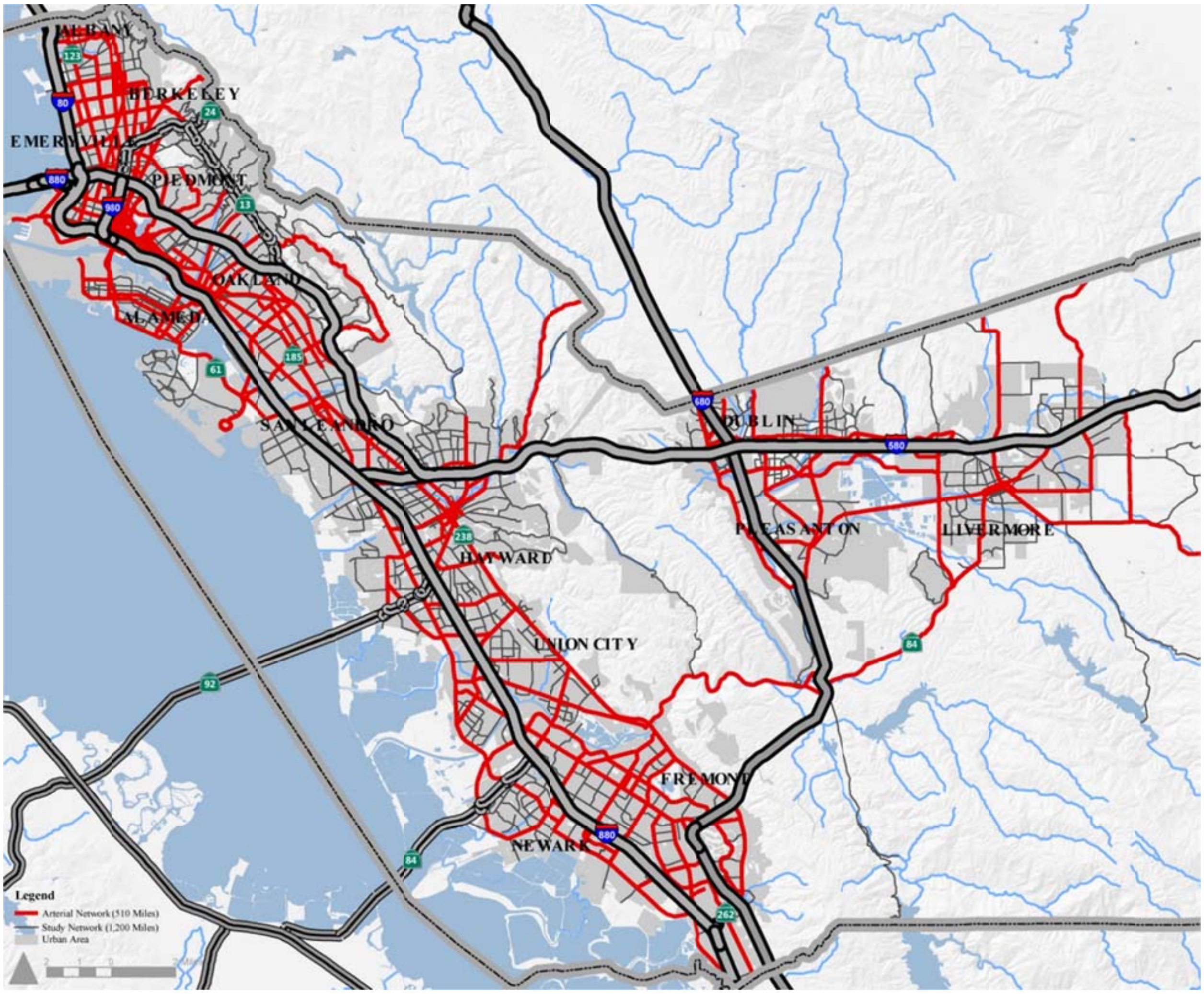

FIGURE 2 Alameda Countywide Study Network and Arterial Network Map.

Database Platform

Given the scale of this study, a platform to effectively manage the data was needed. The Study Network, Arterial Network, and all associated data are managed in an ArcGIS database platform. This platform served as the strong foundation to manage and consolidate data inputs, storage, and visualization of roadway cross-sections and analysis results. The database allows file compression, rapid data review and queries, scripting automation capabilities, and multiple user accessibility and scaling. Using the ArcGIS platform provided quick and effective visualization, via a series of maps, for a wide audience of analysts and reviewers throughout the process. This platform also provides the ability to visualize data via web-based maps, which is an effective approach for stakeholders to review results and provide comments.

Planning Framework – Typology and Modal Priority

Alameda CTC and the project team along with extensive coordination with all Alameda County jurisdictions developed a countywide planning framework that created a typology for the Study Network based on land use context, modal networks, and automobile trip distance characteristics. The typology provides the foundation for defining the countywide Complete Streets network to determine how streets function for all users. The GIS Tool database incorporated the following typology layers for the Study Network:

- Land Use Context
  - Priority Development (PDA) land use types defined by the Association of Bay Area Governments (ABAG), and
  - Land use types developed in Alameda County's Sustainable Communities Strategies (SCS).
- Transit Network
  - Major corridors,
  - Crosstown routes, and
  - Local routes.
- Pedestrian Network
  - High pedestrian emphasis areas,
  - Medium pedestrian emphasis areas, and
  - Low pedestrian emphasis areas.
- Bicycle Network (*18*)
  - Class 1 multi-use paths,
  - Class 2 bicycle lanes,
  - Class 2 enhanced buffered bicycle lanes,
  - Class 3 bicycle routes,
  - Class 3 enhanced bicycle boulevards, and
  - Class 4 protected bicycle lanes.
- Base Street Type Network (Automobile Network)
  - Throughways (roadways with at least 10,000 ADT and at least 50 percent of ADT travels more than eight miles per trip),
  - County connectors (roadways with at least 10,000 ADT and at least 45 percent of ADT travels more than six miles per trip),
  - Community connectors (roadways with any ADT and at least 50 percent of ADT travels more than four miles per trip), and
  - Neighborhood connectors (roadways with any ADT and at least 50 percent of ADT travels less than four miles per trips).
- Goods Movement Network
  - Tier 2 routes, and
  - Tier 3 routes as identified in Alameda CTC's Goods Movement Plan *(19)*.

Most of Alameda County's arterials have limited ROW and many are not able to accommodate improvements for all modes. As a result, modal priorities were developed for the Study Network to identify the modes with highest priority for improvements. The typology system listed above provided the basis for identifying the modal priorities by layering the networks within the GIS database. The layered networks identified overlapping facility types by mode; these facility types, along with the land use context, were then used to determine the modal priority, from highest to lowest priority mode, for each Study Network segment. With this key information, the GIS Tool is capable of identifying study segments that do not meet performance objectives for high priority modes.

Scenario Focused Evaluation

The GIS Tool was developed with the capability to evaluate multimodal performance and identify needs for multiple analysis scenarios, including:

- Existing Conditions
- 2020 Conditions: Existing Conditions plus planned and funded roadway improvements through 2020.

- 2040 Conditions - Standard Forecasting Scenario: Existing Conditions plus planned and funded improvements through 2040 assuming standard forecasting approach to estimate 2040 traffic volumes.
- 2040 Conditions - Social and Behavioral Trend Scenario: Existing Conditions plus planned and funded improvements through 2040 assuming a lower Vehicle Miles of Travel (VMT) per capita adjustment factor to estimate 2040 traffic volumes due to social and behavioral trends.
- 2040 Conditions - Next Generation Vehicle Scenario: Existing Conditions plus planned and funded improvements through 2040 assuming standard forecasting approach to estimate 2040 traffic volumes and a 20 percent increase in arterial capacity that can potentially result due to significant penetration of next generation vehicles (e.g., connected and autonomous vehicles) within the vehicle fleet (*20*).
- 2040 Conditions – Plus Recommended Improvements Scenario: 2040 Conditions (Standard Forecasting Scenario) assuming recommended multimodal network infrastructure improvements.

The Existing Conditions scenario required the greatest level of effort to evaluate due to the development of the database and the GIS Tool scripts to conduct the needs assessment evaluation. After completing the Existing Conditions database development and GIS Tool scripts, the future year scenarios only required database adjustments to the traffic volume assumptions to account for the future year forecasts estimated using the Alameda CTC Countywide Travel Demand Model and adjustments to the cross-sectional database to account for planned and funded improvements expected to be constructed by year 2020 and 2040. All GIS Tool scripts developed for the Existing Conditions evaluation were then applied to the future year databases for a full evaluation of multimodal network performance.

One of the major benefits of the GIS Tool is that it allows the evaluation of multiple future scenarios at large scale. For this particular study, the project team evaluated three 2040 scenarios to account for a range in potential futures to provide a better understanding of how the arterial system may operate given the uncertainties in future traffic demand and the potential implications of next generation vehicles within the countywide vehicle fleet. The evaluation of multiple futures better informs stakeholders on potential system needs.

Needs Assessment

A series of Python scripts were incorporated into the GIS Tool to evaluate performance measures for each analysis scenario. Performance measures were then compared to the performance objectives established as part of the MAP; roadway segments that did not meet the performance objective for the top two priority modes were considered to have a need for improvement. For example, if the bicycle mode was the top modal priority along a segment and if the segment did not meet the desired bicycle comfort index performance objective, the segment was flagged as having a need for bicycle infrastructure improvements. Because of the GIS Tool, the needs assessment was conducted at a large scale for multiple analysis scenarios and results were stored within the GIS database. Having the ability to evaluate the needs assessment for multiple analysis scenarios not only provides the basis for improvement recommendations but also allows stakeholders to prioritize investments in transportation infrastructure improvements using various desired criteria incorporated within the GIS database.

Multimodal Infrastructure Improvement Recommendations

The GIS Tool incorporated a Python script that utilized the cross-sectional database to determine the amount of available ROW within a study segment. Available ROW was a key consideration in determining the potential for implementing improvements along segments identified as having a need for improvement. The minimum widths of typical cross-sectional elements recommended by various NACTO design guidelines provided the basis for determining available ROW within the existing curb-to-curb width. By incorporating a Python script within the GIS Tool, existing cross-sectional measurements were compared to the minimum recommended widths for specific cross-sectional elements and the difference in width was considered to be the available ROW that could be repurposed for specific improvements by mode. The following are the minimum dimensions assumed for specific cross-sectional elements in the available ROW determination:

- Parking lane width = eight feet
- Bicycle lane width = five feet
- Travel Lane adjacent to the curb = 11 feet
- Travel lane not adjacent to the curb = 10 feet
- Bus lane = 12 feet
- Center median = 10 feet

Available ROW was also determined assuming the potential removal of on-street parking as well as the potential removal of mixed-flow travel lanes. In the case of on-street parking removal, a geographic filter was applied so that a separate available ROW determination was made only if a jurisdiction approved the removal of on-street for the repurposing of ROW. In the case of the mixed-flow travel lane removal, the evaluation was conducted on segments with the potential feasibility for travel lane repurposing. Feasibility was determined based on modal priority and PM peak hour automobile volume-to-capacity ratio. If either transit, pedestrian, or bicycle modes were identified as being in the top two modal priorities, the GIS Tool recommended travel lane removal only if the automobile volume-to-capacity ratio after lane removal would be less than:

- 0.8 if automobiles were considered top modal priority,
- 1.0 if automobiles were considered second priority,
- 1.2 if automobiles were considered third priority, or
- Any value if automobiles were considered fourth of fifth priority.

For example, if bicycles were considered top priority and automobiles second, the GIS Tool would recommend mixed-flow travel lane removal if the corresponding volume-to-capacity ratio would be less than 1.0.

For roadway segments where performance objectives for the priority modes are not being met or are not forecast to be met in the future and where the available ROW determination described above revealed the potential for excess ROW, the project team used the GIS Tool to identify improvements that would require additional ROW. The tool identified potential modal improvements that would allow these segments to best meet the plan's performance objectives for the top two priority modes and could be implemented within available ROW. As described in the proceeding sections, the tool was able to suggest various improvements for each mode, based on priority, to each roadway segment where there is excess right-of-way; however, the tool does not have the human professional judgment required to iterate, where possible, to arrive at the set of improvements that provide the highest possible tier facilities of the two priority modes. For this reason, professional judgement was used to identify the appropriate improvements for Arterial Network segments based on the set of suggested improvements by mode identified by the GIS Tool. Improvements were recommended utilizing the 2040 Conditions - Standard Forecasting Scenario needs assessment as the basis to identify specific improvement types. In this specific study, the supplemental future year analysis scenarios were primarily evaluated to provide stakeholders with additional information to better inform system needs and prioritize investments in transportation infrastructure.

Transit Network Improvements

The GIS Tool also incorporates the ability to recommend specific improvements by mode that can fit within the available ROW assuming NACTO design guidelines as reference. For example, if a study segment was identified as having a need for transit infrastructure improvements, the GIS Tool would recommend the following improvements depending on available ROW:

- Dedicated transit lanes were recommended if a study segment was considered part of a major transit corridor, the travel lane removal criteria described above was met and there was enough ROW to implement minimum 12 ft bus only lanes per direction,
- Bus queue jump lanes were recommended if the combined parking lane and curb lane width were greater than 22 ft, and
- Bus stop curb extensions were recommended by direction if on-street parking was present.

Pedestrian Network Improvements

If a study segment was identified as having a need for pedestrian infrastructure improvements, the GIS tool would primarily recommend the following improvements:

- Addition of sidewalks if sidewalks were not present,
- Widening of existing sidewalks to six feet in residential areas if existing sidewalks are less than six feet wide,
- Widening of existing sidewalks to nine feet in commercial areas if existing sidewalks are less than nine feet wide,
- Curb extensions at intersections along segments with on-street parking,
- Streetscape improvements along segments with painted or raised medians, and
- Implementation of high-visibility crosswalks.

Bicycle Network Improvements

If a study segment was identified as having a need for bicycle infrastructure improvements, the GIS Tool would recommend the following improvements depending on the available ROW:

- Minimum five foot Class 2 bicycle lanes where available ROW ranged between 10 to 13 feet for two-way streets, or between five to six feet for one-way streets;
- Minimum five foot Class 2 enhanced buffered bicycle lanes with two foot buffers where available ROW ranged between 14 to 15 feet for two-way streets, or at least seven feet for one-way streets,
- Minimum five foot Class 4 protected bicycle lanes with three foot buffers were recommended if available ROW was greater than 18 feet for two-way streets, or greater than 8 feet for one-way streets; and
- Class 3 bicycle routes along segments without available ROW to implement dedicated on-street bicycle lanes. Class 3 enhanced bicycle boulevard improvements were also proposed for collector segments with 25 MPH speed limit and one lane in each direction, that are parallel to nearby arterials.

Proposed Class 1 multi-use path improvements were based on stakeholder input, rather than the GIS Tool.

Automobile Network Improvements

Intelligent transportation system (ITS) improvements were the primary type of improvements considered for automobiles in the development of the MAP. The project team did not develop the GIS Tool with the ability to automate the recommendation of specific ITS improvements for segments that were identified as having a need for automobile improvement. Instead, the GIS Tool identified study segments that did not meet PM peak period and/or PM peak hour volume-to-capacity ratio performance objectives. The project team then utilized this data and applied their professional judgement to identify appropriate ITS infrastructure improvements to enhance traffic management along these congested segments. The general type of recommended ITS infrastructure improvement was then incorporated into the GIS Tool database for further evaluation.

Goods Movement Network Improvements

If a study segment was identified as having a need for goods movement improvement and had enough available ROW, the GIS Tool would recommend minimum 12 foot curb lane widths per direction along specified goods movement network routes.

Final Improvement Recommendations

Both the needs assessment and the ROW opportunity analysis described above were utilized to identify specific infrastructure improvements that could be implemented within a study segment's cross-section. During this stage in the process, transportation planners reviewed both sets of analysis results, and made the improvement recommendations by manually reallocating the available ROW to reflect the improvements within a new cross-sectional database that would become the 2040 Conditions – Plus Recommended Improvements Scenario network. For example, if the highest priorities were bicycle then transit, neither mode met its performance objectives, and the GIS Tool determined that there was enough ROW available to implement Class 4 protected bicycle lanes, then the proposed improvement would be to implement Class 4 protected bicycle lanes. If after assuming this improvement the bicycle performance objectives were met and there were additional ROW available, transit improvements could be recommended.

Fehr & Peers reviewed the initial set of proposed improvements informed by the GIS Tool determinations described above to identify potential Arterial Network gaps for each mode that would remain after implementation of the initial set of improvements. Additional multimodal improvements were then identified for lower priority modes in an effort to develop a complete and connected network for each mode:

- Transit Network: Improvements were proposed along Arterial Network segments beyond those that the transit agencies recommended for the Major Corridors.
- Pedestrian Network: Improvements were proposed to enhance pedestrian connectivity to transit around major transit hubs and along transit Major Corridors with recommended transit-only lane improvements.
- Bicycle Network: Improvements were identified along lower priority bicycle segments that are key to building a countywide bicycle network. The Network Connectivity checks also included a review of Class 1 multiuse trails, and non-arterial Class 3 enhanced bikeways that parallel Arterial Network segments.
- Auto Network: ITS improvements were identified along segments with low auto priority but are key segments to managing traffic demand along Arterial Network corridors. ITS improvements were also identified along high priority transit segments that may have low auto priority.
- Goods Movement Network: Curb lane widenings were proposed along the goods movement network regardless of the goods movement priority along those specific segments.

Improvements were recommended for all modes along the 510 miles of Arterial Network segments. Draft improvement recommendations were presented to all city, County and transit agency staff within Alameda County via a series of web-maps. Comments received by jurisdictions were then incorporated by the project team into the GIS database to finalize the improvement recommendations. Overall, the final improvement recommendations listed below were identified with the help of the GIS Tool and extensive coordination with stakeholders.

- Transit network:
  - 21 miles of dedicated transit lanes,
  - 121 miles of bus stop enhancements and traffic signal optimization.

- Pedestrian network:
  - 81 miles of sidewalk enhancements (including 40 miles of new sidewalks),
  - 81 miles of curb extensions at pedestrian crossing locations,
  - 233 miles of crosswalk enhancements,
  - 60 miles of streetscape enhancements, and
  - 130 miles of pedestrian scale lighting improvements.
- Bicycle network:
  - 34 miles of Class 2 bicycle lanes,
  - 12 miles of Class 2 enhanced buffered bicycle lanes,
  - 37 miles of Class 3 bicycle routes,
  - 25 miles of Class 3 enhanced bicycle boulevards, and
  - 144 miles of Class 4 protected bicycle lanes.
- Automobile network:
  - 226 miles of ITS improvements.
- Goods movement network:
  - 22 miles of curb lane widening along goods movement routes.

Once improvement recommendations were established, the cross-sectional database was updated to reflect those improvements and the performance measure analysis was conducted to evaluate changes in arterial system performance.

Capital Cost Estimates

The project team developed capital unit cost estimates for multimodal infrastructure improvements by reviewing a variety of sources, including recent construction bid documents for projects throughout Alameda County and other readily-available cost databases. The unit cost data was incorporated into the GIS database, which enabled the GIS Tool to estimate capital costs for proposed improvements along specific roadway corridors to provide stakeholders with a general magnitude of costs. Capital cost is one potential criterion that can be used to prioritize projects for implementation.

VISUALIZING CROSS-SECTIONAL IMPROVEMENTS AT SCALE

After the cross-sectional database was updated to reflect improvement recommendations, the project team developed a series of Python scripts to use the database to create thousands of 3D street renderings illustrating before and after improvement conditions. The vision for this task was to have hundreds of cut-sheets for public review so that stakeholders could gain a better understanding of the changes being proposed and where. The process for creating these renderings depended on the use of procedural modeling, whereby complex 3D models can be created at scale based on a predetermined set of rules. For this application, CityEngine was chosen because of its integration with our current GIS database framework, its robust Python application programming interface, and preexisting rules designed to represent multimodal streets that were released in 2014 by Esri. The rule applied to this project was a modified version of the Esri Complete Streets Rule, a CityEngine rule that can represent a substantial portion of the cross-sectional elements within the GIS database, including shared use travel lanes, various bike lane types, bus-only lanes, on-street parking, high-visibility crosswalks, sidewalks, and landscaped buffers or medians. In order to represent both baseline conditions and improvements, the cross-sectional database had to be translated into rule parameters using Python to drive the creation of 3D street renderings. In addition, the network geometry for each segment had to be replaced with simplified lines that shared the exact same physical location and shape. After creating the necessary geometry attributes, the data was imported into CityEngine, which required development of additional Python scripts to automate the geometry generation and rendering processes.

Initially, the scale of the cross-sectional database prevented even high-performance computers from generating the full set of cross-sectional rendering before running out of memory. In response, the rendering scripts were updated so that their generation stages were limited to one cross-section at a time to avoid consuming too much memory. After more than a thousand images were created from the cross-sectional database, the images were integrated into ArcGIS to automate the creation of cut-sheets for each study segment (**Figure 3**).

FIGURE 3 Example Cut-Sheet for Mission Boulevard in Hayward, CA (Proposed Recommendation to Replace On-Street Parking with Class 4 Protected Bicycle Lanes).

CHALLENGES

Developing this first of its kind GIS Tool and database did not come without many unique challenges. The primary challenges were associated with network segmentation, database scenario duplication and cross-sectional data accuracy. Many data sets were developed in separate data layers with varying study segment lengths and limits. The greatest challenge was consolidating the various data layers into a georeferenced master network database. The various data layer networks had different segment limits compared to the master network, making it difficult to consolidate the layers into geographical database and maintain the integrity of the data. To overcome this challenge, an extensive merging tool was developed in ArcGIS Model Builder to combine multiple data layers by interpolating both data collection and geospatial information into a singular master network from all the input networks. All GIS Tool scripts operated under the assumption that they all started from this master network for each scenario that was evaluated.

During the course of the analysis, the GIS tool evaluated six unique analysis scenarios and each required multiple iterations to evaluate. A new network file had to be constructed and validated to match that data schema required by the GIS tool for each analysis scenario. To overcome the challenges with evaluating multiple scenarios, the GIS Tool was developed with the capability batch process multiple networks to maintain consistency and efficiency during the course of multiple analysis iterations.

The project team had to rely on readily-available data to perform the large-scale evaluation. Cross-sectional data was the most critical as it provided the basis for the evaluation and improvement recommendations. Online aerial imagery, which can range from a few months to a few years old, was the primary source for cross-sectional data. As a result, study segments that have been recently improved may have not been reflected accurately in the database. To overcome this challenge, the project team conducted an extensive stakeholder review process by developing a series of web-based maps displaying the geo-databases, thus allowing stakeholders to review and provide their local knowledge to confirm data accuracy.

The original vision for the GIS Tool was to fully automate the reallocation of available ROW to reflect recommended improvements for high priority modes. Due to challenges in developing the extremely complex Python scripts and constraints in schedule, the original vision of a fully automated ROW reallocation was not achieved. Instead, the semi-automated GIS Tool was developed, which required the transportation planner to utilize the GIS Tool suggested recommendations to manually reallocate the ROW to reflect recommended improvements within the GIS database.

CONCLUSION

The GIS Tool developed for the Alameda Countywide Multimodal Arterial Plan was critical in evaluating multimodal network performance at scales not previously feasible. The ability to generate 3D street renderings for small or large scale applications provides stakeholders a powerful tool to review complex technical analysis results in easy to view format. The GIS Tool methodology and analysis approach presented in this paper provides a model framework for public agencies to utilize the latest innovations in technology, big data and performance metrics to guide decision makers with investments in transportation infrastructure.

Several assumptions incorporated into the GIS Tool were developed specifically for the MAP study in effort to reflect local context. The GIS Tool and analysis framework provides the flexibility to customize assumptions to allow the application in other cities and counties. For example, if a public agency decides to develop a similar cross-section evaluation tool, they can choose to incorporate a different set of modal priorities, performance measures, performance objectives and criteria to identify available ROW in an effort to evaluate multimodal network performance. Other agencies can utilize a similar tool for various purposes, including but not limited to evaluating multimodal network performance and needs, identifying infrastructure projects for potential implementation, performing capital cost estimates and prioritizing projects. As transportation planners continue to deal with large uncertainties with planning assumptions about future transportation networks, such as the impacts of next generation vehicles or potential changes in demographics, the ability to orient visualization, communication, and analysis strategies around uncertainty will be critical to informing transportation decisions in the 21st century. The greatest benefit of the technical framework presented in this paper is the ability to evaluate and visualize multimodal networks at large scales and for multiple scenarios accounting for the ranges in future year uncertainties.

Like many analysis tools, there is a desire to continue to expand the GIS Tool's capabilities for future applications. Potential improvements include the full automation of improvement recommendations and ROW reallocation within the database, as well as improvements to the network and database management process to minimize varying study segment limits between different data sets. The GIS Tool can also be updated to incorporate additional unit cost data to estimate maintenance and operating costs for specific arterial corridors. The unprecedented development of the GIS Tool provides the foundation for future applications in other regions of the country with the opportunity to continue to expand the tool's analysis capabilities. The project team is hopeful that this innovative cross-section evaluation tool will further evolve multimodal planning efforts and that other agencies will employ and enhance the tool's capabilities.

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