Relating Transportation Systems Management and Operations Strategies to Policy Goals: A Framework for Quantitative Decision Making

David Hurwitz, Oregon State University
Kevin Heaslip, PE, Utah State University
Derek Moore, Oregon State University

Abstract: In an effort to maximize the use of limited funding due to decreasing tax revenue, transportation agencies across the country are giving greater consideration to low cost strategies as a means of addressing transportation problems. The majority of these strategies can be grouped under what is sometimes termed Transportation System Management and Operations (TSMO) strategies. This research effort develops a decision making framework that quantifies the strengths and weaknesses of select TSMO strategies relative to specific transportation policy goals. Previously, the limited availability and quality of performance measure data for individual strategies, a lack of consensus as to what performance measures are most appropriately mapped to a particular policy goal, and a lack of consistency between the performance measures associated with individual TSMO strategies have prevented a quantifiable assessment of TSMO performance. This work has conducted an extensive search for both national and local TSMO data sources that were reduced into a usable form. A four step decision making framework is then proposed and demonstrated on an example that includes four strategies and policy goals. This work provides a clear and user-friendly approach for transportation managers and decision makers to quantify the selection of one TSMO strategy over another.

Keywords: Transportation Management, Transportation Planning, Transportation Decision Making, TSMO

EMJ Focus Areas: Operations Management, Quantitative Methods & Models

In an effort to maximize the use of limited funding, transportation agencies across the country are giving greater consideration to low cost strategies as a means of addressing transportation problems. The majority of these strategies can be grouped under what is sometimes termed Transportation System Management and Operations (TSMO) strategies. TSMO strategies can be further categorized as (1) Transportation Demand Management (TDM), (2) Intelligent Transportation Systems (ITS), or (3) Transportation System Management (TSM) strategies.

The Oregon Transportation Plan (OTP) and Oregon Highway Plan (OHP) promote various TSMO strategies as effective ways to manage different aspects of the transportation system. For example, the OTP highlights the importance of applying TDM strategies to "reduce peak period travel, help shift traffic volumes away from the peak period, and improve traffic flow (ODOT, 2006)," and the OHP emphasizes an operational need for additional investment in ITS strategies that can "increase safety, increase travel time reliability, and relieve congestion especially in congested metropolitan areas (ODOT, 1999)." While TSMO strategies have been recognized as potential solutions to transportation problems, a comprehensive decision making framework that quantifies how TSMO strategies perform in relation to competing transportation policy goals does not exist. Previous work by Bilec et al. (2010) has identified similar challenges in the assessment of environmental health, where until recently only single cause and single effect impacts had been considered. Several factors have prevented the development of such a framework in the past, specifically, the limited availability and quality of performance measure data for individual strategies, a lack of consensus as to what performance measures are most appropriately mapped to a particular policy goal, and a lack of consistency between the performance measures associated with individual TSMO strategies.

From these conclusions, it was apparent that research was needed with the objective of developing a decision making framework that quantifies the strengths and weaknesses of select TSMO strategies relative to specific transportation policy goals for the Oregon Department of Transportation (ODOT). The objectives of this project support the notion that transportation engineering management in government agencies has been underserved as compared to private industry (Kern, 2002). In order to improve the state of the practice, a systematic approach to gathering information, evaluating the gathered information, and providing stakeholders with timely recommendations in a quantitative framework was necessary.

In fulfillment of the goals of the project, several activities were undertaken. The first activity was to examine statewide policy and planning documents to identify transportation policy goals that could be potentially impacted by TSMO strategies. Next, a list of TSMO strategies was generated, highlighting several strategies that were both of interest to ODOT, and associated with local data sources. Data were then investigated in an attempt to quantify each TSMO strategy in relation to one of several transportation policy goals. Results from this effort are presented, including a decision making framework for determining the quantifiable impact of evaluated TSMO strategies in relation to transportation policy goals, resulting in a ranked ordering of the strategies for a given context. To provide additional clarity, the framework is demonstrated through an example including four strategies and four goals, but it can be expanded to as many strategies and goals as may be warranted by a particular situation.

Identification of Transportation Policy Goals

The research team reviewed the most recent versions of significant planning documents developed by transportation agencies in Oregon, which might contribute to the identification of transportation policy goals that are of priority in Oregon. Seven primary transportation planning documents were reviewed. These included documents concerned with particular modes of

Refereed Research Manuscript. Accepted by Special Issue Editor Long.

transportation (ODOT, 1992, ODOT, 1995, ODOT, 1997, and ODOT, 1999) as well as integrated system documents (ODOT, 2006 and ODOT, 2008).

The documents were initially examined to identify references related to TSMO, TDM, ITS, or TSM and to identify overarching policy goals that might be addressed by TSMO strategies. The four policy goals identified for the purpose of demonstrating the decision making framework included: safety, sustainability, mobility, and accessibility.

The selected transportation policy goals can broadly be defined as follows:

- *Safety* – reducing the risk of death, injury, or property loss for all modes of transportation. Secondarily, public health (e.g., physical activity) is sometimes considered under safety.
- *Sustainability* – meeting present needs without compromising the ability of future generations to meet their needs. The system is operated, maintained, and improved on the basis of positively affecting both the natural and built environments. (In Oregon, one of the major sustainability initiatives underway is the establishment of greenhouse gas (GHG) emission reduction targets.)
- *Mobility* – quickly moving people and goods to their destinations. The mobility policy identified in the Oregon Highway Plan specifies its measurement as a volume to capacity ratio (v/c).
- *Accessibility* – providing connectivity to people and places through an integrated multimodal system. Assuring access to regional, national, and international markets, as well as those within communities.

Identification of TSMO Strategies

A list of TSMO strategies was developed from the TSMO appendix in the ODOT Transportation System Planning Guidelines (2008), the TSMO toolbox developed for Metro (2008), and in consultation with the ODOT planners and engineers. Strategies identified from these sources were investigated for general data location, availability, and format in an effort to determine which TSMO strategies may be measurable and predictable for the four selected ODOT policy goals. The four TSMO strategies identified for the purpose of demonstrating the decision making framework included: bike/pedestrian infrastructure, park and ride, incident management systems, and ramp metering.

The selected TSMO strategies can be broadly defined as follows:

- *Bike/Pedestrian Infrastructure* – bicycle and pedestrian facilities include any facility that accommodates non-motorized transportation such as walking, bicycling, and small wheeled transportation such as skateboards (Victoria Transportation Policy Institute, 2010).
- *Park and Ride* – park and ride facilities typically provide surface lots for individuals to park their vehicles and join carpools or some form of public transit, thereby removing single occupancy vehicles (SOVs) from the roadway and reducing congestion (Caltrans, 2010).
- *Incident Management Systems* – traffic incident management systems are developed to ensure a rapid, efficient, and coordinated response to traffic incidents. Building on previously established definitions, incidents will describe accidents, breakdowns and other random events that occur on the highway system (Bertini et al., 2001).
- *Ramp Metering* – ramp metering describes a system that regulates the input flow of vehicles onto a freeway. Working much like a traffic signal, vehicles must stop when the ramp meter is red while one vehicle is allowed to enter the motorway during each green phase.

Literature Review

This literature review addresses two primary questions: (1) What operational strategies should be selected based on the availability and robustness of the accumulated data sets at the state and national level? (2) What transportation policy goals should be considered against which to compare those strategies? The methodology was developed to quantify potentially dozens of strategies across multiple policy goals, but for simplicity, this initial demonstration will be concerned with four policy goals (mobility, accessibility, sustainability, and safety) and four strategies (bike/ped infrastructure, park and ride, incident management systems, and ramp metering), which were determined to be of particular interest in Oregon. As such, the following subsections provide an abbreviated description of the data sources, both local and national, that were acquired for each strategy.

Bike/Pedestrian Infrastructure

Cervero and Radisch (1995) compared travel characteristics in an old, compact, and mixed-use neighborhood in the Oakland, OR, region (Rockridge), and Lafayette, OR, a comparable automobile-centric community with suburban tract housing. Separate surveys for work and non-work trips (4000 each) were sent to randomly selected households in both areas. With response rates of 21% for work trips and 15.5% for non-work trips, the survey results revealed that for non-work trips of one mile or less, Rockridge residents made 15% fewer vehicle trips and 22% more walking trips than Lafayette residents. For trips of one to two miles, 15% were made by non-auto means in Rockridge, while only 7% were made so in Lafayette. For work trips, 69% of Lafayette's commute trips were found to be SOVs versus 51% of Rockridge commute trips. Around 6% of Rockridge's commuters travelled by bus, while none of those surveyed in Lafayette did. Bicycling (4%) and walking (7%) were also more popular means of commuting in Rockridge than those in Lafayette (0% and 1% respectively). They also found the mode choice to be dependent on trip purpose as Rockridge residents had 20% fewer automobile trips for shopping purposes in comparison with Lafayette's residents (Cervero and Radisch, 1995).

In 2009, two bicycle facilities were installed in downtown Portland that involved removing a motor vehicle lane to provide additional space for bicycles. One involved building a cycle track that was separated from vehicular traffic by a row of parked cars and a pedestrian buffer. The other involved building a couplet of buffered bike lanes with a painted buffer on either side. One year after the installation, surveys were conducted to evaluate the facilities and 18 hours of video observations were also conducted at each location to confirm the survey results.

For the cycle track, a sample of 148 motorists, 124 bicyclists, and 198 pedestrians were surveyed. Over 70% of survey respondents indicated that the cycle track made cycling safer and easier, and improved the cycling environment. When comparing to the prior traditional bicycle lanes, results showed that concern about the risk of being "doored" by a motor vehicle was substantially lower in the cycle track (36% vs 95%). Also, the percentage of bicyclists riding in the motor vehicle lane decreased from 12% to 2%; however, some of the respondents expressed concerns about the loss of access for disabled people who tend to park or drop-off at the curb (Monsere, McNeil, and Dill, 2011).

Moreover, in terms of bicyclists-pedestrians conflict, over 40% of cyclists stated they had been involved in a near-collision with a pedestrian, while 12% of pedestrians stated they had been involved in a near-collision with a bicyclist. Higher potential for conflicts was also confirmed by the video data. For the buffered bicycle lanes, a sample of 114 motorists, 125 bicyclists, and 35 businesses were surveyed. Respondents indicated they used the buffered bicycle lanes more often (65%), which was consistent with the 77% increase found by the video counts. Bicyclists indicated that the buffered bicycle lanes were safer and that they were less concerned about being "doored." Nearly 9 in 10 bicyclists preferred a buffered bike lane to a standard lane. From the motorists' point of view, however, 61% found driving on these streets to be less convenient. Fifty-six percent also indicated that parking was more challenging and nearly 50% indicated that traffic and travel times had increased. Forty-six percent of the businesses surveyed supported the buffered bicycle lanes, while 26% did not. Most of the respondents indicated that the buffered lanes make parking more challenging for customers (Monsere, McNeil, and Dill, 2011).

Federal statistics of bicycling levels in different countries show greater bicycle use in European countries such as the Netherlands, Germany, and Denmark, when compared to the U.S. It has been postulated that one of the contributing factors to higher bicycle use in Europe, especially among women, children, and the elderly, is the provision of safer bicycling facilities. While safer facilities can encourage more bicycling, the provision of more bicycle facilitates also improves safety thereby encouraging bicycle use. Fatality rates per trip and per kilometer traveled are much lower for countries and cities with a high bicycle mode share, and fatality rates typically decrease as bicycle mode share increases. From 2002 to 2005, the average number of American bicyclist fatalities per 100 million kilometers cycled was 5.8 compared with 1.7 in Germany, 1.5 in Denmark, and 1.1 in the Netherlands (Pucher and Buehler, 2008).

Park and Ride

In San Francisco, CA, a survey was conducted of users of 35 park and ride facilities (including a mix of 32 Caltrans, city, county, transit agency lots, and three BART stations). The survey results were aggregated by corridors and sub-regions. The results showed that almost all park and ride users were commuters (98%) and began their trips at home (94% to 97% depending on the corridor), 67% to 93% were "habitual users" using the same lots four days a week or more, 93% to 100% of the users drove alone to lots and only 4% to 7% rode with someone else or used other modes of transport (Shirgaokar and Deakin, 2005).

Another weekday survey of 1,100 inbound passengers at the Bristol-Brislington, UK, park and ride showed that 70% were commuters; however, on a Saturday, 78% of users were shoppers. Users were asked how they would have travelled to the city center without a park and ride facility. In response, travelers said that on a week day 54% would have driven and 40% would have used public transport. Conversely, during the weekend, 70% said they would have driven to the city center and 18% said they would have used public transport. Additionally, on the weekend 4% said they would have gone elsewhere and 8% said they would not have made the trip at all (Hewett and Davis, 1996).

An evaluation study of 26 park and ride lots in the Seattle metropolitan area was conducted by the Washington State Department of Transportation (WSDOT) using 6,138 surveys, out of which 39.1% were returned. The surveys included questions about origin and destination, trip purpose, frequency of park and ride use, transportation mode used to and from the facilities, and users' alternate mode options in the absence of park and ride lots. The results showed that park and ride lot usage increased person travel times (minutes/person trip) by 13.3% and miles traveled (miles/person) by 3.9%. The results also showed a 21.3% reduction in fuel consumption (gallons of gas/person trip) and 35.5% in accident costs (dollar equivalent/person trip). Moreover, they found 1.3% reduction in traffic volume (vehicle trips/day), 0.5% reduction in vehicle miles traveled (VMT) (miles/day), 0.16% reduction in nitrogen oxides (NOx), 0.12% reduction in hydrocarbons, and 0.09% reduction in carbon monoxide (CO) (grams/day). A cost comparison between the average previous mode trip and the after park-and-ride trip was also performed on 467 cases. It was determined that on average, the park and ride users' travel costs are 7% to 12% less expensive than the previous mode trip. Overall, the authors suggested that, although park and ride facilities slightly increased the length of trips and travel time for individuals, they have positive impacts on the air quality and the efficiency of the transportation system (Rutherford and Wellander, 1986).

Incident Management Systems Data

Facilitating incident management was one of the primary objectives for the installation of five closed circuit televisions (CCTV) at "high priority" intersections in New York. A 120 day evaluation following the installation used detailed incident logs to track incidents at locations with and without CCTV. The evaluation reported that incident validation times were reduced by 50% to 80% at locations with CCTV compared to those without, which resulted in savings of 5 to 12 minutes in response time (Bergmann, 2006).

An evaluation was performed by the University of Missouri on the Freeway Motorist Assist (MA) Program in St. Louis. This program is a critical part of a larger incident management program and focuses on patrolling the interstates in and around St. Louis. This program is responsible for clearing stalled vehicles and debris from the roadway as well as quickly identifying incidents and assisting emergency personnel. By making assumptions and estimating the number of crashes if the MA program had not been implemented, the evaluation estimated that the program reduced the number of secondary crashes by 1,082 annually (Sun et al., 2009). By a similar approach it was also estimated that the delay associated with incidents would have been 89% to 125% higher without the Motorist Assist Program.

A study in Seattle, Washington, examined the impacts of integration of incident and traffic management systems with advanced traveler information systems. This study used EMME/2 and INTEGRATION 1.5 as the planning and simulation models, respectively. The results showed an overall decrease of 1.9% in the number of crashes and a 0.6% decrease in fatal crashes. Moreover, results showed that the system could lower the number of stops by 4.7% and improve travel time reliability by 1.2% in sub-areas (Wunderlich et al., 1999).

Since 1995, ODOT's Region 2 has operated one of the first incident management programs outside of a major urban area (Bertini et al., 2001). Research results show that this program has reduced the duration of incidents by 31% on Highway 18 and 14% on Interstate 5. It also reports that the average delay per incident, as well as the associated fuel consumption and emissions, was reduced by 66% and 36% for Highway 18 and Interstate 5, respectively (Bertini et al., 2001).

Ramp Metering Data

In 2006, the Wisconsin DOT accumulated the results for common Measures of Effectiveness (MOEs) from many ramp metering implementations throughout the country, including projects in Minneapolis (I-35), Portland (I-5), Seattle (I-5), Long Island (Multiple), Detroit (I-94), Denver (I-25), and others. Based on this summary, ramp metering resulted in speed increases of 8% to 61%, and travel time changes from an increase of one minute to a decrease of 12 minutes. Ramp metering also resulted in a crash reduction of 5% to 50%, and a flow increase of 2% to 86% (Rafferty and Treazise, 2007). This document simply provides a summary of the results, with no information regarding the methods of collecting and reporting the results, which could contribute to the large variations seen in the ranges provided.

In 2000 legislation required that a study be done to evaluate the effectiveness of ramp meters located on roughly 210 freeway miles in the Twin Cities, MN, region. An empirical pre/post study was conducted by collecting field data during the same time of day with the ramp meters on, and then off. This study found that ramp metering resulted in a systemwide annual savings of over 25,000 hours in delay and improved travel time reliability by saving 2.6 million hours of unexpected delay (Systematics, 2002). Associated with the reduction in delay, the study estimated an annual savings of 1,160 tons of emissions and 22,246 gallons of fuel (estimated to be a 5.8% reduction).

Data Collection

Two primary sources of data were considered for this study: (1) national data sources evidenced by technical reports to transportation agencies and university based research, and (2) local data sources (in this case *local* was defined as the state of Oregon, but the proposed model is scalable to any geographic area) that were either maintained or managed by transportation agencies.

While the literature review was primarily concerned with national data sources, in person interviews were required with numerous transportation agency personnel to successfully identify and acquire local data. These local data supplement the national information either by providing a ground truth of the national results or by adding new information where national data was determined to be scarce. As each potential data source was identified, it was evaluated to determine its accuracy, form, and relationship to the selected TSMO strategies and transportation policy goals. Past research and evaluation efforts conducted by various public agencies, private consultants, and academicians were used as examples of how these data sources could be reduced to specific performance measures that could be mapped to transportation policy goals.

It was most desired to obtain data in a raw, original form such that additional reduction and analysis could be possible. Ownership, privacy issues, and loss of original data precluded this possibility in some instances. Organized by the TSMO strategy they support, Exhibit 1 provides an abbreviated summary of the Oregon-specific data acquired for this demonstration.

Exhibit 2 presents the ranges of data acquired from multiple national and local sources for each strategy organized by each policy goal of interest. Data types displayed in regular text were identified from national sources while data sources identified in italics were acquired from local sources. All of the data were manipulated into percent reductions for a particular measure. The format of Exhibit 2 is consistent with previous efforts to organize metrics with different performance outcomes (Bilec, 2010).

Decision Making Framework

The framework described within this section provides a systematic approach for the mapping of selected TSMO strategies to transportation policy goals. Ultimately, unique numbers will be determined for each individual strategy, which reflects its impact across several policy goals of varying priority. The framework is designed to provide a simple analysis that can be shared and implemented with technical personnel, politicians, and citizens in a manner that is user friendly and accessible to all stakeholders.

In order to have an "apples to apples" comparison of the data collected, the various MOEs of concern are converted to percent changes and then reduced to a single number. To generate the

Exhibit 1. Summary of Available TSMO Data Sources Identified in Oregon

Strategy	TSMO Classification	Data Source	Available MOEs	Policy Goals Addressed
Bike/Ped Infrastructure	Transportation Systems Management	-Cycle Track infrastructure evaluation by Portland State University (survey and video data)	-Bicycle trip frequency -User satisfaction -Vehicular delay	-Mobility -Sustainability
Park and Ride	Transportation Systems Management	-Data analysis from TriMet surveys of the park and ride districts in Oregon	-Commute trips -Mode shares	-Mobility -Sustainability
Incident Management Systems	Intelligent Transportation Systems	-OSP Computer Aided Dispatch (CAD) database -ODOT Crash Analysis & Reporting Unit database	-Congestion/delay -Fuel consumption -Air quality -Customer Satisfaction	-Mobility -Sustainability -Safety
Ramp Metering	Intelligent Transportation Systems	-PORTAL: Archived loop detector data including vehicle counts, speed, weather, and incidents	-Speed, travel time, delay -Vehicle miles traveled -Vehicle hours traveled -Fuel consumption -Emissions	-Mobility -Sustainability - Safety

Exhibit 2. Summary of Acquired TSMO Data from National and Local Sources

TSMO Strategy	Mobility		Accessibility		Sustainability		Safety	
	Measure	Data	Measure	Data	Measure	Data	Measure	
Bike/Ped	Reduced SOV Trips	18%	*Walking Increase*	*2%*	Eco Mode Choice		Cyclist Fatalities	4.1-
	Reduced # Trips		*Cycling Increase*	*5%*	*Safety Perception*	*3%*		
			Bike Parking Demand	*3%*				
Park and Ride	Reduced # Trips	1%	Transit Increase	77%	Reduced Fuel Con.	21%	Reduced Crash Cost	33%
	Reduced VMT	0.5%	*Transit Increase*	*17%*	Reduced User Cost	27%		
	Reduced TT	-13%						
	Reduced PMT	-4%						
Incident	Reduced Delay	89-125%			*Reduced Fuel Con.*	*33-66%*	Reduced Crash Rate	2%
	Reduced # Stops	5%			*Reduced Emissions*	*33-66%*	Reduced Fatal Crashes	1%
	Reduced TT Variability	1%					Red. Validation Time	50-80%
	Reduced Delay	*33-66%*					*Red. Incident Duration*	*14-31%*
Ramp Metering	Reduced TT	20-48%			Reduced Fuel Con.	5.8%	Reduced Crash Rate	
	Increased Travel Speed				Reduced NOX	5.8%		
	Increased FW Flow							
	Reduced Delay	*Up to 55% or neg.*						

single number, a diminishing returns approach was used to provide a more conservative estimate of the impact of a single strategy on a single policy goal. This approach minimized the additive effects of including several MOEs in a single strategy policy pair. If the percentage impact cannot be determined because of non-quantitative values, it should not be used.

The framework shows how much of a positive or negative influence a selected measure provides to the selected policy goal. As has been described in the previous work of Youngblood and Collins, it can often be difficult to weight one performance measure over another (2003). In order to be conservative, the lowest impact value was used for a study that reports results with a range of values. In addition, if there are multiple studies referenced, the mean value of the studies was used.

Framework Overview

The steps of the framework include the development of context dependent tables that will inform local policy stakeholders of the relative impact of TSMO strategies on transportation policy goals. The framework can be broken down into four primary steps. Brief descriptions of the steps follow:

- *Step I: Prioritize Policy Goals* – Develop a prioritization of the policy goals for the particular transportation problem being addressed. The prioritization of evaluation criteria is a critical element in decision making (Botta, 2007). In some instances policy goals are equally important; however, situations may arise where they are not. As an example, a situation may exist where a particular source of funding must be expended to reduce emissions, thereby emphasizing sustainability over other goals.
- *Step II: Choose Projects for Analysis* – The initial sieve analysis organizes the polarity of each strategy in relation to each policy goal based on aggregate national data sources. This sieve will utilize the prioritization of policy goals from Step I to select the most appropriate strategies. The initial sieve removes strategies that are less attractive so that further analysis is more efficient. This saves the analyst from conducting a full comparison of all strategies that might be considered when

there are really a handful of top contenders for the problem at hand. It is envisioned that when dozens of strategies are added, significant time savings will result. The output of this step will be a selection of projects for further analysis.

- *Step III: Adjust Data Based Upon Source* – The impact of individual strategies on each transportation policy goal is determined. The impact is assessed by considering national and local data sources with local data having three times the influence on the weighted impact calculation.
- *Step IV: Assess Strategy Impact* – The determination of a unique score is calculated for each strategy. This unique score is determined as a weighted average which includes the priority of the transportation policy goals based upon the problem definition as well as the magnitude of impact for each strategy on each transportation policy goal.

Step I: Prioritize Policy Goals

Like many aspects of transportation planning and engineering, this initial step is dependent on an accurate definition of the problem to be addressed. With an appropriate appreciation for the problem, the relative priority for each ODOT policy goal can be established. The ranking of each priority can range from 0% to 100%, where 0% represents no importance regarding the problem at hand and 100% represents the entirety of the problem at hand. It is envisioned that many multi-dimensional problems will require a distribution of priorities across multiple policy goals. The sum total of the relative importance measures should be 100%. Exhibit 3 displays an example of the weight matrix for four policy goals. This measure could be expanded to encompass additional policy goals of interest.

Step II: Filter Potential Strategies and Choose Projects for Analysis

The second step is to determine the direction of impact of a given strategy. This step is important because filtering can be accomplished quickly by a policymaker based upon the polarity of the impact on the policy goal. The policy goals should be rank ordered based upon the results of Step I. Strategies with negligible or negative relations to policy goals can be remove from further consideration. Exhibit 4 shows an example of the matrix for Step II.

Step III: Adjust Data Based Upon the Source of the Data (National or Local)

The literature review clearly shows that the performances of many TSMO strategies are context dependent, meaning that the implementation results vary significantly depending on the in-situ conditions. Oregon specific data will be given three times priority over data collected from other national studies, based on anecdotal evidence. The determination of the appropriate multiplier will be a future study. If there is no local data, then the data from national sources shall be used without adjustment. If there is only local data, then the local data shall be used without adjustment. If there are data from both local and national studies, the local data shall be weighted three times the national data. If there are ranges of data, then best and worst case scenarios should be considered. Positive values should be assigned to desired impacts and negative values should be given to detrimental impacts. The percentage should be expressed in a whole number. Equation 1 describes the mathematical relationship between local and national data when calculating the Adjusted Impact.

$$\text{Adjusted Impact} = \left[3 \times (Local\ Data) + (National\ Data)\right] / 4 \qquad (1)$$

Step IV: Assess Strategy Impact on Each Policy Goal

The final step constructs a "TSMO Score" for each strategy. This calculation allows us not only to determine how each strategy contributes to a cross section of prioritized policy goals, it also provides a means for comparing individual strategies to one another. The proposed weighted average equation is given as Equation 1. The multiple impacts model is adapted from a

Exhibit 3. Example Weighting Matrix for Policy Goals

Policy Goals	Relative Importance
1	P_1 %
2	P_2 %
3	P_3 %
4	P_4 %
…n	P_n %
	∑ Relative Importance = 100%

Exhibit 4. Example Matrix Showing the Direction of Influence for Each Strategy

Policy Goals	TSMO Strategies				
	1	2	3	4	…n
1	+	-	-	0	
2	0	+	-	0	
3	-	0	0	+	
4	+	0	0	-	
…n					

methodology proposed by Roy Jorgensen and Associates and presented by Garber and Hoel (2008). The first part of the process is to sort the impacts by most impactful to least impactful and then perform the following calculation.

Step IVa: Rank and Sort the Impacts

Rank and sort the impacts of each strategy by policy goal. The following list represents all of the measures that were collected from national and local sources for a particular strategy (Exhibit 5).

Step IVb: Calculate the Total Policy Impact Strategy

Find the impacts of the strategies on each of the policy goals. The formula comes from a modified version of a crash reduction factor proposed by Roy Jorgensen and Associates and presented by Garber and Hoel (2008). This formula is powerful because it can distinguish between different types of impacts, and provides a factoring of diminishing returns on the influence of multiple impacts. Equations 2, 3, and 4 describe the calculation for the total impact of a strategy on a policy goal if there are one, two, or three available MOEs.

$$\text{Total Policy Impact}_{1\text{ MOE}} = I_1 \tag{2}$$

$$\text{Total Policy Impact}_{2\text{ MOEs}} = I_1 + (1 - I_1) \times I_2 \tag{3}$$

$$\text{Total Policy Impact}_{3\text{ MOEs}} = I_1 + (1 - I_1) \times I_2 + (1 - I_1) \times (1 - I_2) \times I_3 \tag{4}$$

Where

I_j –The impact of MOE j related to policy goal I

Step IVc: Calculate the TSMO Score

Find the total TSMO Score for each strategy. Equation 5 shows that the total TSMO Score is calculated as the relative importance of the Policy Goal multiplied by the Total Policy Impact of a particular strategy on a particular policy goal.

$$\text{TSMO Score} = (PG_1 \times TI_1) + (PG_i \times TI_i) \tag{5}$$

Where

PG_i - Weight of Policy Goal i
TI_i - Total Policy Impact on Policy Goal i

Illustrative Example of Framework

The following example demonstrates the application of the proposed four step decision making framework by considering the relative performance of four TSMO strategies (bike/ped infrastructure, park and rides, incident management systems, and ramp metering) across four transportation policy goals (mobility, accessibility, sustainability, and safety).

The initial step requires the analyst to prioritize the importance of each policy goal for the particular situation being considered. In this example, mobility and safety have been determined to be of equivalent priority relative to one another (35%), but of a comparatively higher priority than accessibility and sustainability which are both specified at 15%. The relative importance of policy goals defined in Step I of the framework is displayed in Exhibit 6.

In Step II, a single impact number is established for each measure that has been collected for each policy goal. All measures are converted to percent reductions. For those individual measures that include ranges, the lower bound is selected as the most conservative value. The impacts for every measure are included in Exhibit 7. Visual inspection can be used to potentially eliminate an individual strategy at this step. In this case the ramp metering strategy can be removed based on the relatively small impacts when compared to the other strategies.

Exhibit 5. Example of Sorted Performance Measures

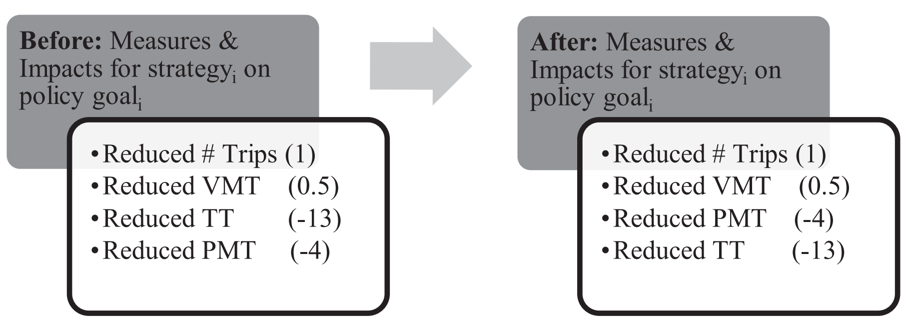

Exhibit 6. Prioritized Policy Goals (Step I)

Policy Goals	Relative Importance (%)
Mobility	35
Accessibility	15
Sustainability	15
Safety	35
Total	100

Exhibit 7. Choose Projects for Analysis (Step II)

TSMO Strategy	Mobility		Accessibility		Sustainability		Safety	
	Measure	Impact	Measure	Impact	Measure	Impact	Measure	Impact
Bike/Ped Infra-structure	Reduced SOV Trips	18	*Walking Increase*	*2*	Eco Mode Choice	6	Cyclist Fatalities	4.1
	Reduced # Trips	9	*Cycling Increase*	*5*	*Safety Perception*	*1*		
			Bike Parking Demand	*1*				
Park and Ride	Reduced # Trips	1	Transit Increase	77	Reduced Fuel Con.	21	Reduced Crash Cost	33
	Reduced VMT	0.5	*Transit Increase*	*17*	Reduced User Cost	23		
	Reduced TT	-13						
	Reduced PMT	-4						
Incident Manage-ment Systems	Reduced Delay	89			*Reduced Fuel Con.*	*33*	Reduced Crash Rate	2
	Reduced # Stops	5			*Reduced Emissions*	*33*	Reduced Fatal Crashes	1
	Reduced TT Variability	1					Red. Validation Time	50
	Reduced Delay	*33*					*Red. Incident Duration*	*14*
~~Ramp Metering~~	~~Reduced TT~~	~~20~~			~~Reduced Fuel Con.~~	~~5.8~~	~~Reduced Crash Rate~~	~~5~~
	~~Increased Travel Speed~~	~~8~~			~~Reduced NOX~~	~~5.8~~		
	~~Increased FW Flow~~	~~2~~						
	~~Reduced Delay~~	~~0~~						

In Step III an adjustment is made to calibrate national data with local data where consistent measures were identified. The calculation of an Adjusted Impact, where the local measure is weighted three times that of the national measure, is described in Equation 1. An example of the calculation for the park and ride accessibility measure of transit increase is as follows:

$$\text{Adjusted Impact}_{TransitIncrease} = \frac{[3\times(17)+(77)]}{4} = 32$$

In this example, adjusted impacts are calculated for the park and ride accessibility measure (transit increase) and the incident management systems mobility measure (reduced delay). Both adjustments can be seen in Exhibit 8 where the national and local data are crossed out in favor of an adjusted impact which is underlined.

In Step IVa, the impacts of each strategy on each policy are organized largest to smallest. Exhibit 9 displays the ranked impacts for each TSMO strategy.

In Step IVb, a Total Policy Impact is calculated to relate each individual strategy to each transportation policy goal as a diminishing return calculation. The calculation for two data types is described in Equation 3, and an example of the calculation for the bike/ped infrastructure Total Policy Impact on mobility (rounded to the nearest whole number) is as follows:

$$\text{Total Policy Impact}_{\text{Bike/Ped Mobility}} = [0.18+(1-0.18)\times 0.09]\times 100 = 25$$

The Total Policy Impacts for each strategy on each policy goal for the example are displayed in Exhibit 10. The highest total policy impact observed in this example appears between incident management systems and safety. This is a logical outcome as the intended purpose of incident management systems is the identification and clearance of crashes to mitigate the likelihood of secondary crashes.

In Step IVc, a single TSMO score is calculated for each individual strategy as a weighted average. The calculation is described in Equation 5 and an example of the calculation for the bike/ped infrastructure TSMO Score (rounded up to the nearest whole number) is as follows:

Exhibit 8. Adjust for Local Data (Step III)

TSMO Strategy	Mobility		Accessibility		Sustainability		Safety	
	Measure	Impact	Measure	Impact	Measure	Impact	Measure	Impact
Bike/Ped Infra-structure	Reduced SOV Trips	18	*Walking Increase*	*2*	Eco Mode Choice	6	Cyclist Fatalities	4.1
	Reduced # Trips	9	*Cycling Increase*	*5*	*Safety Perception*	*1*		
			Bike Parking Demand	*1*				
Park and Ride	Reduced # Trips	1	~~Transit Increase~~	~~77~~	Reduced Fuel Con.	21	Reduced Crash Cost	33
	Reduced VMT	0.5	*~~Transit Increase~~*	*~~17~~*	Reduced User Cost	23		
	Reduced TT	-13	<u>Transit Increase</u>	<u>32</u>				
	Reduced PMT	-4						
Incident Manage-ment Systems	Reduced # Stops	5			*Reduced Fuel Con.*	*33*	Reduced Crash Rate	2
	Reduced TT Variability	1			*Reduced Emissions*	*33*	Reduced Fatal Crashes	1
	~~Reduced Delay~~	~~89~~					Red. Validation Time	50
	~~Reduced Delay~~	*~~33~~*					*Red. Incident Duration*	*14*
	<u>Reduced Delay</u>	<u>47</u>						

Exhibit 9. Rank and Sort the Impacts by Order of Impact (Step IVa)

TSMO Strategy	**Mobility**		**Accessibility**		**Sustainability**		**Safety**	
	Measure	**Impact**	**Measure**	**Impact**	**Measure**	**Impact**	**Measure**	**Impact**
Bike/Ped Infrastructure	Reduced SOV Trips	18	*Cycling Increase*	5	Eco Mode Choice	6	Cyclist Fatalities	4.1
	Reduced # Trips	9	*Walking Increase*	2	*Safety Perception*	*1*		
			Bike Parking Demand	1				
Park and Ride	Reduced # Trips	1	<u>Transit Increase</u>	<u>32</u>	Reduced User Cost	23	Reduced Crash Cost	33
	Reduced VMT	0.5			Reduced Fuel Con.	21		
	Reduced PMT	-4						
	Reduced TT	-13						
Incident Management Systems	<u>Reduced Delay</u>	<u>47</u>			*Reduced Fuel Con.*	*33*	Red. Validation Time	50
	Reduced # Stops	5			*Reduced Emissions*	*33*	*Red. Incident Duration*	*14*
	Reduced TT Variability	1					Reduced Crash Rate	2
							Reduced Fatal Crashes	1

Exhibit 10. Find the Impacts of the Strategies on Each Policy Goal (Step IVb)

Strategy	Mobility	Accessibility	Sustainability	Safety
Bike/Ped Infrastructure	25	8	7	4
Park & Ride	1	32	39	33
Incident Management Systems	50	0	55	59

Exhibit 11. Find TSMO Score for Each Strategy (Step IVc)

Strategy	Score
Bike/Ped Infrastructure	13
Park & Ride	23
Incident Management Systems	46

$$\text{TSMO Score}_{\text{Bike/Ped Infrastructure}} = (0.35\times 25)+(0.15\times 8)+(0.15\times 7)+(0.35\times 4)=13$$

The final TSMO Score for each strategy included in the demonstration are presented in Exhibit 11. As can be seen in Exhibit 11, the framework results in a recommendation of incident management systems as generating the best performance in relation to the prioritization of transportation policy goals selected in this example.

Conclusions

This research effort develops a decision making framework that quantifies the strengths and weaknesses of select TSMO strategies relative to specific transportation policy goals. Significant efforts were taken to acquire and reduce performance measure data from transportation agencies and researchers around the country. A four step decision making framework was then proposed and demonstrated on a four strategy by four transportation policy goal hypothetical situation. This work provides a simplistic approach for transportation managers and decision makers to quantify the selection of one TSMO strategy over another while influenced by a spectrum of transportation policy goals. Specifically, managers can implement the approach described when considering transportation improvement project alternatives to produce a clear and publicly defendable selection of a TSMO strategy. Historically, these decisions have been more ambiguous and, therefore, more difficult to defend publicly. The following subsections describe the strengths, potential limitations, and possible future work in the development of the framework.

Framework Strengths

The proposed framework has several inherent strengths. It is scalable in nature. This paper provided a demonstration that mapped four TSMO strategies to four transportation policy goals, but the framework could compare dozens of goals with dozens of strategies, assuming the model could be populated with a critical density of data. Often when transportation managers are tasked with evaluating alternative TSMO strategies, the assessments rely on qualitative comparisons. This work proposed a quantitative comparison grounded in data that should result in more easily defendable solutions. The inclusion of national and local data provides for a calibration to the conditions that exist within the jurisdiction of a particular transportation agency. The dimensionless comparison eliminates the complication of inconsistent measures that relate a single strategy to multiple policy goals. Finally, the ultimate product is a single number that allows for the ranking of individual strategies that can be easily interpreted by both technical and non-technical stakeholders.

Framework Limitations

The primary limitation of the proposed framework is associated with the amount and variety of data required to support effective transportation decision making. MOE data may not be readily available for many of the TSMO strategies that are of interest to a particular transportation agency, as large numbers of comprehensive studies have not yet been performed. Even when a particular study can be identified, it likely only involved one or two MOEs, making it more difficult to map to all of the policy goals under consideration. The model calibration is accomplished with the integration of local data sources; however, this data tends to be distributed across numerous agencies that may or may not be willing to readily share this information.

Potential Future Work

The potential impact and versatility of the proposed framework could be increased if the volume and context of the national and local data was expanded upon. The integration of larger data samples could increase user confidence in the results of the framework. The scalable nature of the local versus national (three to one) requires supplemental calibration that could be achieved with this more comprehensive data set.

If the adjacent landuse or roadway function classification could also be considered for a particular MOE, the potential to implement the model in a variety of contexts would be improved. The challenge here is the difficulty imposed by data acquisition as limited reliable sources are available for certain TSMO strategies that are of particular interest.

References

Bergmann Associates, "I.T.S. Camera Deployment and Systems Integration Evaluation," *Monroe County Department of Transportation* (2006).

Bertini, Robert, Sutti Tantiyanugulchai, "Evaluation of Region 2 Incident Response Program Using Archived Data," *Oregon*

Department of Transportation. (No. PSU-CE-TRG-01-01) (2001).
Bilec, Milissa M., Mathew Geary, Robert J. Ries, Kim LaScola Needy, "A Method for Quantifying the Benefits of Greening a Healthcare Facility," *Engineering Management Journal*, Vol. 22, No. 3 (2010). pp. 3-11.
Botta, Rick, "A Prioritization Process," *Engineering Management Journal*, Vol. 19 No. 4 (2007). pp. 20-27.
California Department of Transportation (Caltrans), "Park and Ride Program Resource Guide," (2010).
Cervero, Robert and Carolyn Radisch, "Travel Choices in Pedestrian Versus Automobile Oriented Neighborhoods," *UC Transportation Center*, UCTC 281 (www.uctc.net) (1995).
Garber, Nicholas J. and Lester A. Hoel, *Traffic and Highway Engineering*, 4th Edition, Thomson Engineering (2008).
Hewett & Davis, Presentation to CPRE Park and Ride Conference "Park and Ride in the Context of an Integrated Transport Strategy for the former Avon Area," *Bristol City Council* (1996).
Kern, David J., "Content and Trends in Engineering Management Literature," *Engineering Management Journal*, Vol. 14, No. 1, (2002), pp. 43-48.
Monsere, Christopher, Nathan McNeil & Jennifer Dill, "Evaluation of Innovative Bicycle Facilities: SW Broadway Cycle Track & SW Stark/Oak Street Buffered Bike Lanes (Final Report)," *Center for Transportation Studies, Portland State University*, (2011).
Oregon Department of Transportation. 1995. *Oregon Bicycle and Pedestrian Plan*.
Oregon Department of Transportation. 1999. *Oregon Highway Plan: An Element of the Oregon Transportation Plan*.
Oregon Department of Transportation. 1997. *Oregon Intelligent Transportation System Strategic Plan.*
Oregon Department of Transportation. 1997. *Oregon Public Transportation Plan*.
Oregon Department of Transportation. 1992. *Oregon Rail Passenger Policy Plan*.
Oregon Department of Transportation. 2006. *Oregon Transportation Plan*.
Oregon Department of Transportation. 2008. *Transportation System Planning Guide*.
Pucher, John and Ralph Buehler, "Cycling for Everyone, Lessons from Europe," *Transportation Research Record: Journal of the Transportation Research Board, No. 2074* (2008), pp. 58 - 65.
Rafferty, Peter, and Marie Treazise, "Wisconsin Ramp Metering Operations and Implementation," *Proceedings of the 2007 Mid-Continent Transportation Research Symposium*. Ames Iowa, (2007).
Rutherford, Scott G. and Chris A. Wellander. "Cost Effectiveness of Park-and-Ride Facilities in the Puget Sound Area," *Washington Department of Transportation* (1986).
Shirgaokar, Manish and Elizabeth Deakin, "Study of Park-and-Ride Facilities and Their Use in the San Francisco Bay Area of California," *Transportation Research Record: Journal of the Transportation Research Board, No. 1927*, (2005). pp. 46 - 54.
Sun, Carlos, Venkat Chilukuri, Tom Ryan, and Micheal Trueblood, "Final Report: Evaluation of Freeway Motorist Assist Program," *University of Missouri* (No. OR10-018, FHWA MO-2009-004) (2010).
Systematics Inc., Cambridge, "Mn/DOT Ramp Meter Evaluation-Phase II Evaluation Report," *Minnesota Department of Transportation* (2002).
Victoria Transportation Policy Institute, "Nonmotorized Transportation Planning, Identifying Ways to Improve Pedestrian and Bicycle Transport," *TDM Encyclopedia* (January 2010).
Wunderlich, Karl, James Bunch, and James Larkin, "ITS Impacts Assessment for Seattle MMDI Evaluation:Modeling Methodology and Results," *Federal Higway Administration* (1999).
Youngblood, Alisha D. and Terry R. Collins, "Addressing Balanced Scorecard Trade-off Issues Between Performance Metrics Using Multi-Attribute utility Theory" *Engineering Management Journal*, Vol. 15, No. 1, (2003), pp. 11-17.

About the Authors

David Hurwitz is an assistant professor in the Department of Civil and Construction Engineering at Oregon State University, and he serves as the point of contact for the Driving and Bicycling Research Laboratory. He is interested in the integration of user behavior in the design and operation of transportation systems. He teaches classes at the graduate and undergraduate level in highway engineering, traffic operations and design, isolated traffic signals, and driving simulation.

Kevin Heaslip, PE, is an assistant professor in the Department of Civil and Environmental Engineering at Utah State University, and director of the Transportation Infrastructure Management and Engineering Laboratory (TIMELab). He is also the associate director of the Utah Transportation Center, a member of the Mountain Plains Consortium. He received his PhD in Civil and Environmental Engineering from the University of Massachusetts, Amherst.

Derek Moore, EIT, recently graduated with an MSCE from the School of Civil and Construction Engineering at Oregon State University. His primary research interests include transportation safety and operations, with an emphasis in driver behavior and signalized intersection performance.

Contact: David Hurwitz, Oregon State University, School of Civil and Construction Engineering, 101 Kearney Hall, Corvallis, OR 97331; phone: 541-737-9242; david.hurwitz@oregonstate.edu