Performance Assessment of Multi-Modal Traffic System Using Micro-Simulation Methods

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ABSTRACT

The purpose of this paper is to define a methodology to evaluate the performance of a multi-modal traffic signal system. Previous studies have concentrated on performance assessment for each mode. The methodology presented in this paper considers an integrated approach to multi-modal performance assessment. An intersection in the Maricopa County Department of Transportation’s SMARTDrive testbed is analyzed using the VISSIM micro-simulation model to study the effects of different designs and signal timing strategies on several performance measures for both vehicles and pedestrians. A tool, called a Multi-Modal Performance Dashboard, is developed to visualize the relationship between various performance measures and multiple modes. Dashboards can be used to characterize the performance of an existing system and also to compare before and after studies when a new design is implemented. Radar diagrams are the basic element of the Multi-Modal Performance Dashboard tool and are constructed for individual performance measures, e.g. passenger vehicle travel time, transit delay, pedestrian volume, and truck stops, and for each movement at an intersection. Based on the results of this study, choosing an appropriate control strategy can impact the different movements of different modes (including pedestrians) in a variety of ways. The more modes involved in the system, the more challenging it is to determine the proper control strategy. Using this tool, alongside statistical models, makes it easier for decision makers to understand, visualize, and analyze data.
INTRODUCTION

Capital improvements to transportation systems, such as rebuilding an intersection, arterial, or corridor, need to be evaluated in terms of the improvements or impacts to the users of the system. Traditional studies have focused on performance measures such as vehicle delay and travel times for a single mode (e.g., passenger vehicles). Recently, there has been a greater focus on mobility and safety of multi-modal travelers— including passenger vehicles, pedestrians, trucks, transit, and emergency vehicles. While performance assessment studies for each mode exist, there is nevertheless a need for a comprehensive approach to multi-modal performance assessment. This paper presents an integrated approach to multi-modal performance assessment.

The study utilizes methods of visualization of multi-modal performance measures that can be presented in an easy-to-understand format to gauge and compare different ways of treating all the users of the system. For visualizing, at a glance, the relationship between different measures and multiple modes, a tool is being developed which reflects the performance of an intersection. This tool utilizes radar diagrams as the basic element, similar to safety viewgrams (1) (a diagram used for safety assessment), and is not intended to replace statistical analysis and modeling. This tool could be used concurrently with other techniques for analyzing the strengths and weaknesses of the existing system. Not only is this tool useful for presenting the results to stakeholders to show them where the benefits and impacts exist, but it is also useful for assessing before and after studies.

The first step in any improvement project is to identify the project objectives and to define appropriate performance measures and metrics. A transportation improvement project may include widening an arterial corridor to provide additional capacity and reduce travel time and delay for vehicles, but this may impact pedestrians. Inclusion of traffic signal priority for transit (or other vehicles such as trucks) could impact both vehicles and pedestrians. There is a need to understand how improvements to one mode may impact, or benefit, another mode.

Frequently, improvement projects have focused on improving vehicular traffic performance. This could be an effective objective for many corridors, but in environments where there is a high pedestrian demand (urban locations), the delays that traffic flow improvements impose on pedestrians might be ignored by existing policies (2). These types of strategies can impact pedestrian traffic in a negative way and may result in unbalanced assessment, especially in central city areas.

Selecting performance measures that properly reflect the project objectives is critical to the success of the assessment. Poor outcomes are most probably results of poor selection of measures (3). Based on the fact that one of the basic requirements of transportation system management is balancing the needs of all users and multiple transportation modes (4), this study uses both multi-modal and mode-specific measurements not only to evaluate the total effect but also to recognize individual deficiencies. This study considers four different road users with the performance measures as follows: transit delay, truck stops, passenger vehicle travel time, and pedestrian volume;

This study utilizes the Maricopa County Department of Transportation’s SMARTDrive testbed, to demonstrate the multi-modal performance assessment methodology. The testbed consists of six intersections along a major arterial corridor in Anthem, AZ. One of the intersections is analyzed using the VISSIM micro-simulation model to study the impacts of alternative signal timing strategies on several performance measures for both vehicles and pedestrians.

The organization of the remainder of the paper is as follows: A brief literature review of pedestrians and their impact on a multi-modal system is presented in the next section; a description of the network and general assumptions used in all the simulations are then explained; the scenarios for designing pedestrian crosswalks considering different signal phasing and timings are then presented in detail; the performance measure visualization methods used to assess multi-modal performance measures are presented using a sample key diagram; and finally, an analysis of results followed by conclusions and recommendations are discussed.
LITERATURE REVIEW

Historically, the principle concern of many studies has been vehicular traffic associated with a single scenario. Models are developed and analyzed for stage- or phase-based optimization of signalized intersections for conflicting streams of vehicle flows, but without explicitly considering pedestrian flows and delays (2).

There have only been a few examples of studies that consider pedestrian travel costs in the design of traffic signal systems. Noland (5) focused on the potential differences in signal-timing options that would follow from consideration of pedestrian delay and also collected some empirical data in London to determine if optimal signal cycles were being applied in practice (6). These studies considered only fixed time signal control and didn’t address issues associated with actuated traffic signal controls.

Many studies have analyzed interactions between pedestrians and turning vehicles at signalized intersections from a safety point of view (7, 8). A LOS (Level Of Service) model for signalized intersections regarding the safety risk based on pedestrian and vehicle demand was introduced by Zhang and Prevedouros (9). In their paper, the conflicts between the movement of through vehicles and the movement of permitted left-turning vehicles and pedestrians were considered. Hubbard et al. (10) studied the interaction between pedestrians and vehicles caused by concurrent right-turning vehicles (right turning on green) at signalized intersections. However, such work has not been extended to consider the impacts of turning vehicles on pedestrians in terms of other performance measures (e.g. delay, travel time, and number of stops for different modes of vehicles).

Urbanik, et al. (11) conducted a complete assessment of different split-phasing options considering pedestrian crossing treatments. The main focus of their study was on the impact of various split-phasing alternatives and alternative pedestrian treatments on traffic operations. Tian et al. (12) studied four different pedestrian timing treatments including (a) no pedestrian timing consideration, (b) pedestrian timing concurrently with vehicle phases, (c) a special pedestrian overlap phase, and (d) an exclusive pedestrian phase.

Considering the geometric layout and control types, there are different kinds of pedestrian control strategies that are possible at signalized intersections. Some of the common ones are fixed-time pedestrian operation, coordinated operation, and push-button actuation (13, 14). Lead and lag phasing on the side street of an intersection have been investigated as a way to lessen the impacts of pedestrians on coordinated signal systems (15).

In the German Traffic Control and Traffic Safety Guidelines for Traffic Signal (16), three different categories for signalization of two successive pedestrian crosswalks were introduced based on local boundary conditions or other given determinations of traffic operations: Simultaneous Signalization, Progressive Signalization, and Separate Signalization. It is recommended that the two successive crosswalks can be treated as two independent crosswalks only if the width of the central refugee island is more than 4 m.

MICRO-SIMULATION NETWORK DESCRIPTION

Based on a traffic simulation software comparison study (17), micro-simulation is a more accurate tool mainly because it uses driver behavior models to simulate the movement of individual vehicles on a network. Another advantage of this type of simulation is that it gives each vehicle an exclusive and realistic performance characteristic while traveling through the network. Version 5.4 of VISSIM was used in this study due to its 3-D and graphical presentation (animation) capabilities (18). Kaseko et al. (19) concentrated on its pedestrian modeling capabilities that are useful for analyzing the pedestrian and vehicle interactions in an urban traffic environment.

Four different modes were considered in the model: passenger vehicles, pedestrians, buses, and trucks (Heavy Good Vehicles - HGVs). Figure 1(a) shows the layout of the four-legged intersection with eight movements. The main street (Daisy Mountain Drive) consists of 3 lanes in each direction, and the side street (Gavilan Peak Parkway) consists of 2 lanes in each direction. Each lane is 11.5ft wide, and the
central refugee island is 13.5ft wide. In order to capture vehicle queues during congested conditions, the roads were extended 800ft beyond the intersection. The mean pedestrian speed was set to 3.5ft/s in all crosswalks.

**Pedestrian Crossing Scenarios**

Before introducing the three alternative pedestrian phasing strategies to be evaluated, it’s necessary to mention that in all the following scenarios, the selected split-phasing design is Protected Left-Turn Arrow Display. Based on a previous study (12), from a driver’s point of view this type of design is preferred and requires that a green arrow be displayed while the approach has the green phase. Also, from a safety point of view, protected left-turns can eliminate the conflicts between the left-turning vehicles and pedestrians. Figure 1(b) shows the controller phase and ring configuration associated with all the scenarios. A barrier exists across both rings between groups of conflicting movements such that all phases in the main street must terminate before any phase in the side street starts (20).

**FIGURE 1** (a) Intersection phasing layout, (b) Controller phase and ring configuration

**Scenario 1: Single-Stage Crossing with Pedestrian Timing Concurrent with Phases**

Single-stage crossing refers to the case when the pedestrian crossing is accomplished in one stage without requiring/allowing the pedestrians to wait in a central refugee island (if available). As shown in Figure 2(a), pedestrians are served in parallel with the moving traffic. For example, the pedestrians using the west crosswalk receive a Walk indication concurrently with the adjacent through-vehicle movement (Phase Φ4), and the pedestrian on the other side of the street would be served simultaneously with the
northbound through movement (Phase \( \Phi_8 \)). The dashed right-turn arrow in Figure 2 represents a permitted movement in which the vehicles are required to yield to the pedestrians.

The most common signal indications at crosswalks consist of three main stages: “Walk”, flashing “Don’t Walk” (FDW), and “Don’t Walk”. Safe crossing of the street can be assured when the total amount of time associated with “Walk” and flashing “Don’t Walk” is sufficient for most pedestrians to safely traverse the street. When a pedestrian is detected by push-button actuation control in the system, the phase duration is determined by the maximum of the time required to traverse the crosswalk and the needed time to serve the vehicular traffic.

Scenario 2: Two-Stage Crossing with Simultaneous Signalization

This is the case when pedestrians can traverse the street in two stages; the first stage consists of moving from the sidewalk to the center refugee island and the second stage from the center refugee island to the far side sidewalk. In this case the pedestrian signal heads must be split to control pedestrian movement in each stage. From a signalization standpoint, the signals shown both on the edge of the curb and on the central refugee island should display the same indications, so pedestrians can cross to the central refugee island and wait for the next Walk indication to finish the path. This type of design seems to be more efficient for vehicles and is widely used in some European countries, mainly because the impact of long pedestrian crossing time on phase duration can be minimized. The shorter the length of the crosswalk, the less pedestrian clearance time is needed. Figure 2(b) illustrates the phasing scheme associated with this scenario and depicts the pedestrian phases for both stages. Consider the east crosswalk where pedestrians move concurrently with northbound traffic movement (Phase \( \Phi_8 \)) in two stages. Similarly, the west side of the street moves at the same time with southbound traffic movement (Phase \( \Phi_4 \)).

Scenario 3: Two-Stage Crossing with Combination of Simultaneous and Separate Signalization

By combining two of the main types of signalization, simultaneous and separate (as stated in the literature review), improvements can be applied to the system. Generally, separate signalization refers to the case when the indication for one of two successive crosswalks displays the Walk interval earlier than the other (21). As shown in Figure 2(c), for both stages on each crosswalk, the pedestrian intervals are timing concurrently with their adjacent vehicle through movement (exactly the same as scenario 2). The option added to this design is that the pedestrian timing for one stage of each of the crosswalks can overlap with the left-turning vehicles that do not conflict with the pedestrian movement. For example, for the first stage of the west crosswalk, pedestrians can start walking concurrently with not only the southbound through movement (Phase \( \Phi_4 \)), but also the eastbound left-turn movement (Phase \( \Phi_5 \)). While vehicles are completing Phase 5, there is no conflict between vehicles and pedestrians in the upper stage of the west crosswalk. This makes it possible for both the pedestrians waiting on the northwest corner planning to move south and those on the central island intending to reach the northwest corner to walk simultaneously with eastbound left-turning vehicles.

In this design, the number of pedestrians being served during a cycle increases, and their waiting time decreases. Pedestrians are allowed to walk during two different phases in one cycle and don’t have to wait for the “Walk” indication of next cycle.
Simulation

In this paper, the duration of the simulation is determined to be 60 minutes. The simulation resolution chosen for all the scenarios is 1 second. Based on research conducted by Fellendorf et al. (22), in order to get sufficiently precise results for almost all applications of VISSIM micro-simulation, this resolution is appropriate. 10 different random seeds are considered for replications in order to make allowances for the stochastic variations. All the simulations are conducted with actuated traffic signal controls in favor of getting more realistic results.

The traffic composition used in the simulations is as follows: 84% passenger vehicle, 11% truck (HGV), and 5% transit for vehicular traffic. Various pedestrian flows are considered for different crosswalks, but on average about 170 ped/h have been assumed.
Data collection is done on 4 various measures of effectiveness: delay for transit, number of stops for trucks (HGVs), travel time for passenger vehicles, and for pedestrians. The data output is analyzed in three different levels based on the corresponding objectives, which will be explained in detail after introducing the visualization method.

VISUALIZATION METHOD: RADAR DIAGRAMS

Performance assessment in this paper is a combination of multiple transportation modes and various performance measures in the context of three independent scenarios. Comparing various elements of such multi-modal traffic system under different scenarios would be difficult. Radar diagrams are utilized to visualize performance measures in an easy to read and understand way.

Radar diagrams, which are widely used in the field of organizational development (23), demonstrate multivariate data in the form of a two-dimensional diagram. In the context of transportation, this is a tool that could help monitoring the improvements at intersections. Figure 3(a) is a sample key to the radar diagrams used in this paper. On each axis of this diagram one of the twelve possible movements at an intersection is shown, and the selected performance measure is average travel time in seconds for passenger vehicles on each approach. For example, passenger vehicles on Northbound Right Turn approach spend the least amount of time (17 seconds), and cars on Eastbound Left Turn movement have the most travel time (78 seconds). The diagram shown in Figure 3(b) is a typical bar chart being used to show the results for the same data. In the next section results of different scenarios, various performance measures and multiple modes will be represented using a single radar diagram to demonstrate how to show the outputs of evaluations and comparisons.

![Passenger Vehicle Travel time (s)](a)

![Passenger Vehicles](b)

**FIGURE 3** (a) Sample key to radar diagrams used to describe traffic performance (b) Bar chart used to describe the same traffic performance
ANALYSIS OF RESULTS

As previously mentioned, it is difficult to simultaneously understand the impact of three various design options with four modes in an experiential setting. To address this difficulty, three types of analysis are considered as follows:

- Comparing the performance measures of each scenario for a specific mode and deciding which one of them is the best.
- Assessing the performance measures of one specific phase in different scenarios and then comparing all the measures of different modes related to that phase.
- Comparing performance measures of one mode in one specific scenario, and trying to determine the correlation between the measures related to that mode.

Each analysis has its own objective, which can be achieved by an appropriate review of the associated radar diagrams. Finally, a comprehensive point of view and combination of all these analyses of comparisons is presented in the form of a dashboard as an integrated view of the results.

One Mode, Different Approaches, Different Scenarios

The specific mode being analyzed is pedestrians. Figure 4 depicts how much time, in seconds, it takes for pedestrians to walk from one corner of the intersection to another. For example, average travel time (including waiting times) varies for moving from the southwest corner to the northwest corner under different scenarios. At single-stage crosswalk (first scenario), the average travel time is 103 seconds, while for the second scenario (two-state crosswalk with simultaneous signalization) it increases to 179 seconds, and for the third scenario (two-stage crosswalk with combination of simultaneous and separate signalization) it is 114 seconds.

![Pedestrian Travel Time](image)

**FIGURE 4** Pedestrian travel time including waiting times for different movements and scenarios

Pedestrian travel time for the second scenario (two-stage crossing with simultaneous signalization) has the highest value for almost all the pedestrian movements. The third scenario (two-
stage crossing with a combination of simultaneous and separate signalization) is placed roughly in between the other two, and could be interpreted as the trade-off scenario. The travel time for the second and third scenarios are higher than that of first scenario and the main reason would be that in these two cases, pedestrians have to wait in the central refugee island, which increases their delay and waiting time and subsequently the travel time.

Although the delay of pedestrians in the first scenario is lower than others, this fact should be taken into account that in this case, the number of pedestrians moving from one corner to another in one cycle is smaller than in the third scenario. For example, pedestrian volume in the third scenario moving from the southeast to the northeast corner, on average, is 25% more than that of the first scenario for each cycle, while the difference in travel time is 32 seconds. So, it’s a trade-off between the number of pedestrians served in a cycle and their travel time. From the point of view of travel time, the first scenario is more appropriate (with a small number of pedestrians), and from the point of view of pedestrian volume, the third scenario is preferred. As a result, in urban areas where there is a higher demand of pedestrians, two-stage crosswalks with a combination of separate and simultaneous signalization are recommended. While this analysis focuses on the mobility of pedestrians, the impact to the other modes isn’t highlighted and should also be addressed. The next section considers multiple modes and the impacts of different designs on them.

**One Approach, Different Modes, Different Scenarios**

Among the approaches of the main street to be analyzed, the eastbound through movement is selected. The main reason is that different designs have been applied to the crosswalks of the main street (Daisy Mountain Drive) which has more vehicle demand, so accordingly the impacts of the different pedestrian control strategies where there is a higher probability of interaction between different road users is more interesting.

As shown in Figure 5, two modes are being considered: Trucks (HGVs) and Passenger Vehicles, and travel time and delay are the selected measures.

**FIGURE 5** Eastbound through movement analysis for different scenarios and different modes
The Radar diagram shows that travel time and delay (in seconds) for both passenger vehicles and trucks (HGVs) in the first scenario (single-stage crossing) are higher than that of the second and third scenarios. Generally, considering a measure like vehicle travel time, two-stage crosswalks are better than single-stage crosswalks since the pedestrian intervals are shorter and the signal can cycle faster. In the previous section, it was demonstrated that pedestrian travel time in one-stage crossings had the lowest value, and among two-stage crossings, the third scenario is preferred because of its lower travel time and delay. Again, there exists a trade-off between the travel time of pedestrians and vehicles, depending on the modal demand, and an appropriate strategy could be chosen to achieve the objectives of the system operators. For example, in an intersection where the volume of vehicles is much higher than the volume of pedestrians, a two-stage crossing is recommended. Also, when the street to be crossed is wide, it’s safer to have a two-stage crosswalk (24), and an appropriate phasing design (two-stage crossing with combination of simultaneous and separate signalization) could provide the best service for all road users.

One Scenario, Different Approaches, Different Measures

The main goal of this analysis is to find the strengths and weaknesses within a mode (e.g. passenger vehicles) under a specific scenario, which is selected to be a one-stage crossing in this example. Figure 6 illustrates the correlation between two performance measures: travel time in seconds and vehicle throughput for passenger vehicles.

![Passenger Vehicles 1-stage](image)

The axes of this diagram don’t have specific units, so that both travel time and the number of vehicles can be compared in one diagram. It helps to understand which approach needs improvements or which one serves its demand best. For example, in the last 20-minute time period of the simulation run, in the northbound right-turn movement, although there is a large number of vehicles (112 cars) moving, their travel time is quite short (14 seconds). The primary reason is that there is an independent right-turn lane on this approach, which makes the vehicles move much faster than the other lanes that are required to wait for the next green phase to make the movement. Westbound and eastbound right turn movements have the same situation, but the southbound right-turn doesn’t have a separate lane.

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**FIGURE 6** Passenger vehicles analysis with different measures
This type of diagram could be extended for other scenarios and transportation modes as well. Hence, the concept of a multi-modal transportation dashboard consisting of different radar diagrams was developed to help understand the overall situation of the system better and to assist the decision makers to choose the most appropriate design depending on the actual condition of the intersection and the trade-offs between performance measures, modes, and movements.

Dashboard

When considering the complex interactions of the different transportation modes in complicated intersection geometry, there is a need for a tool showing all the modes at the same time. The dashboard provided in this paper is able to show different measures of various modes under specific scenarios.

Figure 7 is an example of the dashboard under the two-stage crossing with simultaneous and separate signalization scenario but at two different operational hours (peak vs. off-peak). Vehicle and pedestrian demand are assumed to be 825 vehicles per hour per lane and 350 pedestrian per hour per crosswalk during the peak period and to be 325 vehicles per hour per lane and 180 pedestrian per hour per crosswalk during the off-peak period. This dashboard consists of 4 radar diagrams, one for each mode concentrating on the following measures: travel time for passenger vehicles, delay for transit, number of stops for trucks (HGVs), and volume for pedestrians. The pie chart in the middle depicts the distribution of modes in the system.

The impact of peak hour demand on vehicles performance measures is clearly shown. The increase in travel time for passenger vehicles and number of stops for tucks (HGVs) in the southbound through and southbound right-turn movements is significantly more than the increase in the other movements. This shows that there is a bottleneck on this approach during the peak period. Actually, the reason for this observation is that there is no specific right-turn lane for vehicles moving southbound at the intersection.

Figure 8 shows the dashboard consisting of 12 radar diagrams and represents the measures discussed as follows: travel time for passenger vehicles in blue, number of stops for HGVs in orange, delay for transit in green, and travel time for pedestrians in red.
FIGURE 7  Dashboard consisting of four radar diagrams and a pie chart for comparing Peak and Off-peak periods
FIGURE 8  Dashboard consisting of twelve radar diagrams for a comprehensive multi-modal assessment
CONCLUSION

This research has developed a method that can allow the visual assessment of a multi-modal traffic system associated with both vehicular traffic flow and counter-pedestrian flow. An intersection in Maricopa County is analyzed based on three different pedestrian crossing design scenarios. Generally, according to the radar diagrams generated, strategies that benefit the mobility of vehicular traffic may not be beneficial from a pedestrian point of view. There is almost always a trade-off between vehicular and pedestrian measures. Although improving either of these two modes most probably results in impacting the other, ignoring pedestrians in assessments of the system leads to unintended impacts to some of the road users.

Based on the results of this study, in central city locations or any other place where the demand for both vehicles and pedestrians is considered to be high, even in areas that in certain time periods the congestion of pedestrians and vehicles may occur (e.g. near schools or universities), the third design, two-stage crosswalks with a combination of separate and simultaneous signalization, may be the preferred design. First, two-stage crosswalks could benefit the vehicular traffic by providing them lower travel time and delay. Second, a combination of separate and simultaneous signalization for pedestrian signal heads leads to lower waiting time and higher person throughput for each cycle.

In future research studies, different values of time for different modes should be considered, so that more accurate results and better decisions will be made. Also, some of the assumptions regarding the simulation runs could be addressed to reflect a more realistic situation. The performance assessment should be extended to network and corridor measures instead of considering only a single intersection. Finally, taking into account the safety issues associated with crosswalks in urban roads where there is a high demand of pedestrians would benefit this kind of study by offering an even more comprehensive vision.

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