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National Center for Intermodal Transportation for Economic Competitiveness

The Mobility and Safety of Walk-and-Ride Systems

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ABSTRACT

In this project we investigate the effect of traffic calming measures, such as crosswalks and sidewalks on the overall cost and safety of a multimodal transportation network system design. Our design problem includes auto, transit, and walking as modes of transportation. We propose a new method for multimodal user equilibrium (UE) traffic assignment with network reconstruction, which allows for mode switching. We propose a bi-level mathematical programming model that integrates multimodal user equilibrium traffic assignment in the lower level and the network design in the upper level. The model tries to optimally implement and locate sidewalks and crosswalks considering limited financial resources to provide city planners with a comprehensive tool for planning. Due to the complexity of the problem, it requires a large amount of computational resources and therefore cannot be solved efficiently for large scale problems using state of the art solvers; hence we develop a greedy heuristic and a simulated annealing algorithm to solve large problems. The algorithms use a nonlinear complimentary algorithm to solve the UE traffic assignment. The computational results show that implementing sidewalks and crosswalks both reduces the overall transportation cost and improves pedestrians' safety.

Keywords: multimodal transportation network, bi-level programming, complimentary algorithm, user equilibrium, safety.

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INTRODUCTION

In many small communities in the United States, transportation is dominated by a single mode - the motor vehicle. As a result, a lack of infrastructures such as sidewalks and crosswalks pose a safety hazard for underprivileged citizens, as they must walk along busy streets and highways to travel. Since 1920s, there has been a growing attention and interest in pedestrian safety as Campbell et al (Campbell, Zegeer, Huang, & Cynecki, 2004) describe in their review of pedestrians safety research. They claim that pedestrians count for about 40% of all traffic fatalities. In 2010, the Federal Highway Administration (FHWA) estimated that 4,500 pedestrians are killed annually because of traffic accidents with motor vehicles, and as many as 88% of those accidents could have been avoided if walkways separate from travel lanes were available to pedestrians (FHWA, 2010). Not only safety is important for city planners, according to several bodies of literature (Bahari, Arshad, & Yahya, 2013; Weinstein Agrawal, Schlossberg, & Irvin, 2008), it is also important for individual travelers. According to these studies safety of walkways is one of the most important factors to pedestrians regardless of their travel purposes.

To help city planners maximize the benefit of dollars spent on transportation safety, specifically traffic calming, this project presents a mathematical modeling framework for optimizing the allocation of safety resources to a transportation network. We have proposed a mixed integer bi-level programming model that considers both safety and travel costs as objectives and considers where to construction sidewalks and crosswalks. To model the lower level problem in this study we also propose a new method for multimodal user equilibrium (UE) traffic assignment with network reconstruction.

OBJECTIVE

The objective of this research is to investigate the effect of traffic calming measures such as sidewalks and crosswalks on the total travel cost and safety of a transportation network. The model optimizes the usability of the transportation system while ensuring safety. This helps city planners in locating and implementing sidewalks and crosswalks in the transportation network while considering limited budget.

METHODOLOGY

In this study we propose a mathematical programming model for optimizing traffic calming in a multimodal transportation network that includes automobiles, public transit and pedestrians. The problem investigates the effect of traffic calming measures, such as crosswalks and sidewalks on overall cost and safety. The model tries to find the optimal location for city infrastructures considering limited financial resources. To model the problem, we propose a new method for multimodal user equilibrium (UE) traffic assignment with network reconstruction. A nonlinear complementarity algorithm is used to compute the UE. We then model the traffic calming allocation problem as a bi-level transportation network design problem and propose a mathematical programming model. We implement the model in YALMIP (Lofberg, 2004) and solve it using the BARON commercial solver (Sahinidis, 2014). Due to the complexity of the problem, we also develop a greedy heuristic and a simulated annealing algorithm for solving large problem instances.

NETWORK RECONSTRUCTION

According to traffic assignment literature, most of transportation networks are established as a single mode (auto) graph. But, the multimodal traffic assignment proposed in this project is based on network reconstruction. The main goal of network reconstruction is to include all the available modes into transportation network graph as a set of link-modes, where travelers are allowed to transfer between those link-modes when we solve the assignment problem. To explain this process in detail, let $G = (I, L)$ be a directed graph representing an auto transportation network where I and L are sets of auto nodes and directed links, respectively. Let M denote the set of transportation modes in the network. In order to develop a multimodal traffic assignment with network reconstruction, transportation modes will be added to G as a set of link-modes. Three modes of transportation considered in this study: auto, transit and pedestrian. For ease of explanation, the pedestrian mode is demonstrated by two sets of link-modes; crosswalk and sidewalk. Thus, $M = \{'a', 't', 'c', 's'\}$ where $'a'$, $'t'$, $'c'$, $'s'$ represent auto, transit, crosswalk and sidewalk, respectively, and (l, m) is a distinct link-mode in the network in which $l \in L$ and $m \in M$.

The following sets will be used to describe the reconstruction process:

Q: set of intersection nodes, $Q \subset I$

B: set of nodes containing transit station, $B \subset I$

A_i^+: set of outgoing links from node i, $i \in I$

A_i^-: set of ingoing links to node i, $i \in I$

O : set of Origin nodes, $O \subset I$

D : set of destination nodes, $D \subset I$

As mentioned earlier, the reconstruction process is based on a primary auto transportation network graph. To start the process, at first for each intersection node i in primary auto network ($i \in Q$), a number of pedestrian nodes will be added to the neighborhood of node i and they will be connected to each other by crosswalk links. Then, we choose one of the pedestrian nodes as a transfer node, and connect it to the primary network by a transfer link. After that, for each origin destination node in primary network, we add a dummy node to the network and connect it to the main network with a connector link. The transit nodes will be added next and again a transfer link is used to connect the transit nodes to the primary graph. Finally, transit links and sidewalk links are added to the graph. The detailed pseudo-code for reconstruction of $G = (I, L)$ is as follows:

```
for i = 1 : I do
        p_i := ||A_i^+| + |A_i^-||;
        add p_i pedestrian nodes to the network in neighborhood of node i;
        if i ∈ Q:
                add crosswalk links between all p_i pedestrian node around node i;
                from all p_i pedestrian nodes, select t_i as a transfer node;
                add an auto-pedestrian transfer link between t_i and i;
        end if
        if i ∈ O or i ∈ D:
                add a dummy origin-destination node, d_i, to the network;
                add a connector link between d_i and t_i;
        end if
        If i ∈ B
                add a dummy transit node, b_i, to the network
                add a transit-pedestrian transfer link between d_i and t_i;
        end if
for l = 1 : L do
        add a sidewalk link between pedestrian nodes among link l
        add a transit link between transit nodes among link l
end for
```

Note: to capture the pedestrian nodes among link l, we label the them based on their adjacency to link l

To illustrate the algorithm, consider a typical intersection for a single mode (auto) transportation network as shown in **Error! Reference source not found.**. In this figure, node 1 is a cross intersection and nodes 2 to 5 are its neighbor nodes. Nodes 1 to 5 are called "auto" nodes and there are four directed auto links connecting them as well. In order to reconstruct this intersection, at first for every auto node $i \in N$, the pedestrian nodes will be added to the network.

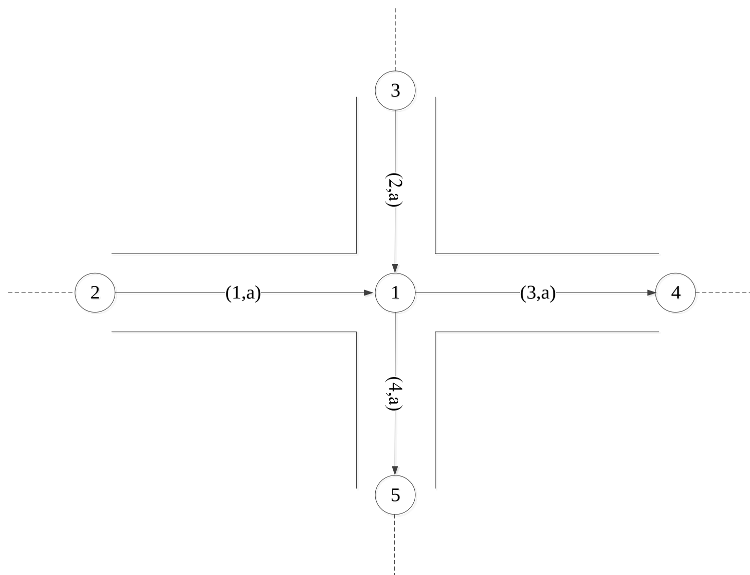
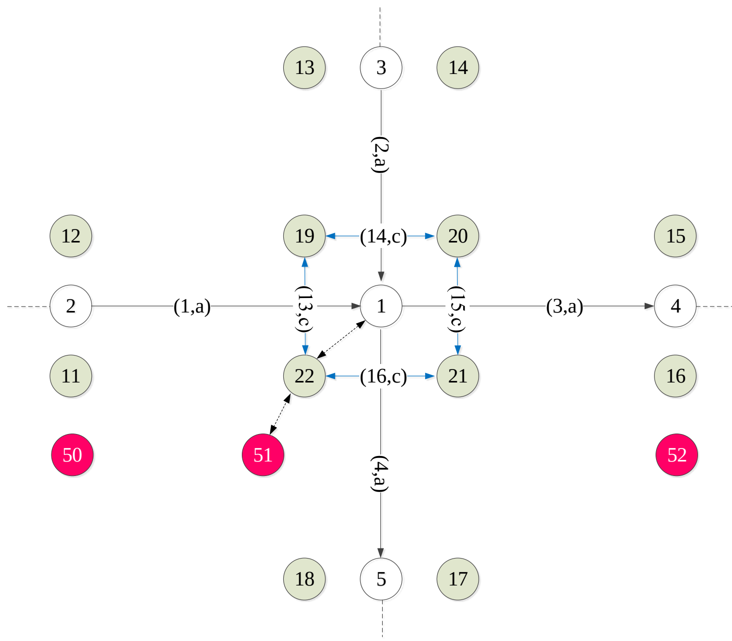


Figure 1 Cross intersection in a single mode transportation network

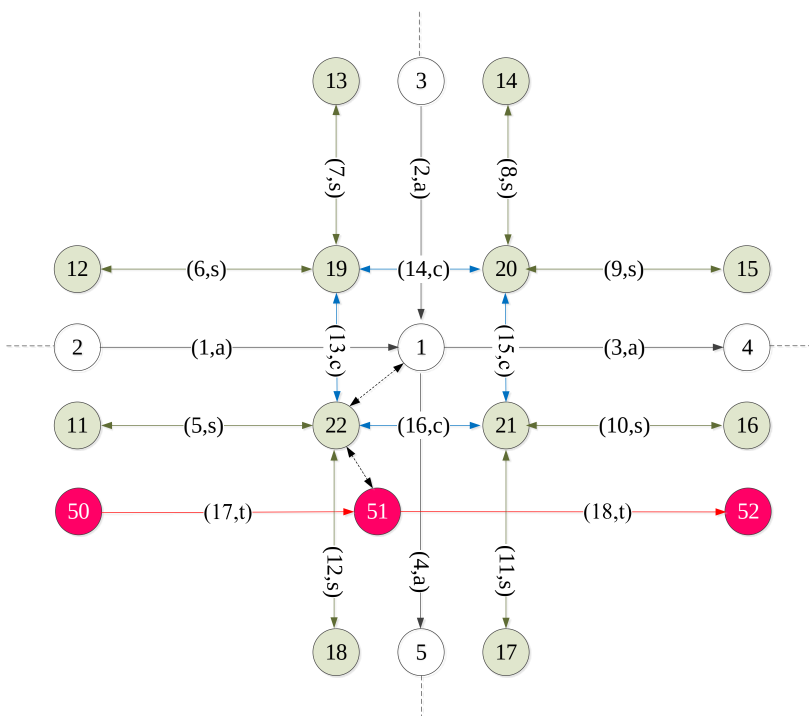
In **Error! Reference source not found.**a nodes 11 to 22 are dummy pedestrian nodes added to the network in green color. Also, in this example $B = \{1,2,4\}$; therefore, transit nodes 51, 52 and 53 are added to the network as well. Since node 1 is the only cross intersection (i.e., $Q = \{1\}$), crosswalk links are added between pedestrian nodes in the neighborhood of node 1, and selecting node 22 as a transfer node between different modes ($t_1 = 22$), there are two transfer links as well. The transfer links are between nodes 1 and 22 for transferring between auto and pedestrian, and between nodes 22 and 51 for transferring between transit and pedestrian (We assume that transfers are only occurred in intersection nodes ($i \in Q$). Also, in order to transfer from transit to auto or vice versa, both of these transfer links should be taken.).

Next, as illustrated in **Error! Reference source not found.**b, every two pedestrian (transit) nodes among the auto links are connected with sidewalk (transit) links. Note that adding sidewalk/crosswalk links between pedestrian nodes does not mean that a physical sidewalk/crosswalk is built between them. Instead, virtual sidewalk/crosswalk links will be added to the network when there is no physical sidewalk/crosswalk in the real network. In this case people can choose to walk on the virtual sidewalk, which often corresponds to walking on the shoulder of a road segment. Also, sidewalk/crosswalk links are bidirectional, meaning means people can walk in both directions regardless of their adjacent auto link direction.

As you can see in **Error! Reference source not found.**b, even for one cross intersection, the reconstruction process needs a lot of effort for adding pedestrian and transit link-modes. In this report, by using a specific numbering format and developing a list structure, we developed an automated procedure to reconstruct the network automatically. The input of reconstruction process is the auto transportation network $G = (I, L)$, and a list of transit stations. Having this information, we can obtain the reconstructed network including pedestrian and transit nodes and links was well as transfer links.



(a)



(b)

Figure 2 Reconstructed process (a) adding pedestrian node, transit nodes, sidewalk links and transfer links (b) adding sidewalk and transit links

In this study we assume travelers can change their transportation mode and alter their route based on their travel cost disutility function. In fact, traffic flows on link-modes in the reconstructed network represent a combined mode choice and traffic assignment based on the generalized travel cost function. In the next section we present the problem of computing the traffic equilibrium on a multimodal transportation network as a nonlinear complementarity problem and then describe the proposed mathematical programming model along with the proposed travel cost function (for more details see Parsafard et al., 2015).

COMPLEMENTARITY ALGORITHM

For the rest of this report the following notations in **Error! Reference source not found.** are used.

Table 1 Notation

Sets and Indices	I:	Set of nodes indexed by $i = 1, \dots, I$
	L:	Set of links, indexed by lm or (i, i') that has six categories, A for auto links, T for transit links, S for sidewalk links, C for crosswalk links, F for transfer links that pedestrian links to auto and transit links, and R for connector link which just connect the network together.
	M:	Set of transportation mode-links, denoted by $m = a, t, p$ where "a", "t", and "p" represent auto, transit, and pedestrian respectively.
	J:	Set of traffic calmings indexed by j, $j = bx, ex, s$, where "*bx*", "*ex*", and "s" are begin-crosswalk, end-crosswalk and sidewalk respectively
	L_l:	Set of links "near" link l, including link *l*.
	J_{la}:	Set of traffic calming available on auto-link $la \in L$.
	K:	Set of OD pairs indexed by *k*
Parameters and Functions	b:	Budget
	ϑ	Value of time
	∇	Cost of pedestrians crash
	θ	Transfer cost for pedestrian mode to auto and transit modes and vice versa
	t_{lm}:	Free-flow travel time for link-mode $lm \in L$
	$d_k, \emptyset_k, \Delta_k$	Demand, origin and destination of trip k
	γ_{lm}:	Capacity of link- mode (l, m)
	$\varphi_{lm}(.)$:	Travel cost function for link-mode $lm \in L$
	δ:	Safety weight that quantifies the travelers' preference between time delay and safety.
	$\alpha_1, \alpha_2, \beta_1, \dots, \beta_6$	parameters
	π_{ik}:	Auxiliary variable, the dual variables of the corresponding shortest path problem.
Variables	$X_{kl'm'lm}$	number of trips on link-mode $l'm'$ which is a neighbor link of link-mode lm, where $lm, l'm' \in L$
	X_{klm}:	number of trips on link-mode $lm \in L$
	X:	(X_{klm}), the vector of flow variables
	Y_{jla}:	1 if traffic calming $j \in J_{la}$ is implemented on auto-link $la \in L$, 0 otherwise
	Y	(Y_{jl}), the vector of traffic calming variables

After reconstructing the network and converting the single auto network into a multimodal link-mode network, we use the complementary algorithm proposed by (Aashtiani, 1979) to solve the lower-level traffic assignment problem, Aashtiani (1979) shows that the UE traffic assignment problem is equivalent to a nonlinear complementarity problem (for detailed information about the nonlinear complementarity algorithm see (Aashtiani, 1979). The complementary algorithm presented by Aashtiani (1979) to solve the UE problem is an iterative procedure consisting of path generation, decomposition, and linearization techniques. In this paper we use a link-list dynamic data structure proposed by (Toobaie, Aashtiani, Hamedi, & Haghani, 2010), which makes the complementary algorithm several times faster than Frank-Wolfe algorithm. Advantages of the complementary algorithm is its speed and the fact that it allows for a general cost function, i.e., the travel cost is a function of all the flows in the network. In our reconstructed network, the travel time on every link-mode $(l, m) \in L$, is not only a function of its own flow, but also a function of flow on its competitor link-modes. By minimizing their perceived travel time, travelers decide about mode choice and route choice at the same time.

Overall, there are six types of link-modes in the reconstructed network including auto, transit, crosswalk, sidewalk, transfer and connector links. We propose a different cost functions for each of the links (link-mode) in the network. (Note that connector links connect dummy Origin-Destination nodes to the transportation network and have a travel cost of zero.) For a multi-modal path $p \in P_w$, the transfer time (cost) between two modes includes the total walking time to reach the transfer station and the total waiting time in transfer station. Here, we assume that transfer cost on each of transfer links is constant. Note that there are two groups of transfer links; auto-pedestrian and transit-pedestrian transfer links; to transfer from transit to auto both of these transfer links must be used.

THE PROPOSED MIP MODEL

The traffic calming optimization problem is formulated as a bi-level problem in which the upper-level problem is the design problem, and the lower-level problem is the problem of travelers who choose their mode and route. The problem is formulated as the following bi-level mixed-integer program.

$$Min \sum_{k\in K} \sum_{(i,i')\in L} \varphi_{(i,i')}(X,Y) X_{k,(i,i')} \tag{1}$$

$s.t.$

$$X_{k,(i,i')}\left(\varphi_{(i,i')}(X,Y) - \left(\pi_{i',k} - \pi_{i,k}\right)\right) = 0 \qquad \forall (i,i')\epsilon L, k\epsilon K \tag{2}$$

$$\sum_{i':(\emptyset_k,i')\in L} X_{k,(\emptyset_k,i')} = d_k \qquad \forall k \in K \tag{3}$$

$$\sum_{i':\,(i',i)\in L} X_{k,(i',i)} - \sum_{i':(i,i')\in L} X_{k,(i,i')} = 0 \qquad \forall i\epsilon I \setminus \{\emptyset_k, \Delta_k\}, k\epsilon K \tag{4}$$

$$\sum_{j\in J} \sum_{(i,i')\in L} c_{(i,i'),j} y_{j,(i,i')} \le b \tag{5}$$

$$X_{k,(i,i')} \ge 0 \;\; \forall k\epsilon K, (i,i')\epsilon L \tag{6}$$

$$\pi_{ik} \ge 0 \;\; \forall k\epsilon K, i\epsilon I \tag{7}$$

$$y_{\,j,(i,i')} \epsilon \{0,1\} \forall j\epsilon J, (i,i')\epsilon L \tag{8}$$

The objective function (1) is to minimize the total cost in the network. Constraints (2) enforce the optimal flow solution to be at travel cost equilibrium. Constraints (3) require that all of the demand flows through the network for every trip. Constraints (4) enforce conservation of flow at all nodes in the network. Constraint (5) is the budget constraint, and constraints (6) to (8) restrict the range of variables.

In order to explicitly include safety in our model, a safety term is added to the travel cost function of sidewalk link. The travel cost function $\varphi_{lm}(.)$ is different for each mode-link based on the type of mode-link. For auto link-modes, $l = (i, i') \in A$, the travel cost function is a function of auto links, sidewalk links, crosswalk links, and transit links as follows:

$$\varphi_{(i,i')}(X,Y) = \vartheta\left(\left(\left(\left(\frac{\sum_{k\in K} X_{ks1pla}}{\gamma_{l'p}}\right)^{\beta_2} + \left(\frac{\sum_{k\in K} X_{ks2pla}}{\gamma_{l'p}}\right)^{\beta_3}\right) \times (1 - y_{s,la}) + \left(\frac{\sum_{k\in K} X_{l'bxla}}{\gamma_{l'c}}\right)^{\beta_4} \times (y_{bx,la}) + \left(\frac{\sum_{k\in K} X_{l'exla}}{\gamma_{l'c}}\right)^{\beta_5} \times (y_{ex,la}) + t_{la}\left(1 + \alpha_1\left(\frac{\sum_{k\in K}(X_{la} + \omega X_{l'tla})}{\gamma_{la}}\right)^{\beta_1}\right)\right)\right) + \mu_{la}$$

For auto links the effect of traffic flows on transit, sidewalk, and begin- and end-crosswalks are also considered. The effect of transit flow on the auto travel cost function includes a bus passenger car equivalent factor (ω). As it matters whether the sidewalks and crosswalks on the auto links are built or not, the associated decision variables are considered as well ($y_{s,la}, y_{bx,la}, y_{ex,la}$). In the case of a built sidewalk ($y_{s,la} = 1$), the flow of pedestrians on the sidewalk usually does not affect the flow on auto links, otherwise pedestrians have to walk on the sides of streets. However, building crosswalks ($y_{bx,la}$ or $y_{ex,la} = 1$) encourage more pedestrians to cross the auto link and interfere with its flow and therefore increase the travel cost for auto. The last term in the auto cost function, μ_{la}, is the out of pocket cost for using the auto link.

For transit links, $l = (i, i') \in T$, the model only includes the effect of flow on auto and transit links. However, as the direct effect of sidewalks and crosswalks are included in the auto travel cost, therefore the travel cost of transit includes the indirect effect of sidewalks and crosswalks. Also transit fare is included into the transfer cost of transit links as shown below:

$$\varphi_{(i,i')}(X,Y) = \vartheta \times t_{la}\left(1 + \alpha_1\left(\frac{\sum_{k\epsilon K}(X_{k,lt} + \tau X_{klalt})}{\gamma_{l,t}}\right)^{\beta_1}\right)$$

The travel cost function for pedestrians on a sidewalk link, $l = (i, i') \in S$, includes a travel cost function similar to the Bureau of Public Roads (BPR) link congestion function but converted to dollar value. It also includes a safety term which computes the expected number of pedestrian crashes on the auto links in neighborhood of the sidewalk link. In the safety term, we used crash data and traffic counts in Starkville, Mississippi, to find the pedestrian crash probability function. For each street in Starkville, we defined a crash probability by dividing the total number of crashes by the total traffic flow on that street. We then used a simple linear regression model, (see Table 2), to calculate the crash probability function, and used the regression model's coefficients to develop the safety term. Thus, the safety term is as follows:

$$\varphi_{(i,i')}(X,Y) = \vartheta(1-\delta) \times (t_{lp} + \alpha_2 \left(\frac{X_{lp}}{\gamma_{lp}}\right)^{\beta_6}) + \delta\left(1 - y_{s,lp}\right) \times \left(\frac{(0.00000017 + 0.00000000036 X_{l'alp}) X_{l'alp}}{0.01 \times \gamma_{lp} \times \nabla}\right)$$

To combine the BPR travel cost function and the safety cost function, an adjustment weight factor δ is used in the model. We refer to this weight factor as the safety weight factor. In this formula ∇ is the cost of pedestrian crashes.

The travel cost function for pedestrians on crosswalk links, $l = (i,i') \in C$, is also a BPR travel cost function:

$$\varphi_{i,i'}(X,Y) = \vartheta \times (t_{i,i',s} + \alpha_2 (\frac{X_{i,i',p}}{\gamma_{l,p}})^{\beta_6})$$

The travel cost function for transfer links, $l = (i,i') \in F$, as shown below, computes the total walking time to reach the transfer station and the total waiting time in the transfer station. This total time is converted to a dollar value by multiplying by the factor ϑ. We assume the transfer cost on each of transfer links is a constant:

$$\varphi_{i,i'}(X,Y) = \vartheta \times \theta$$

The travel cost function for connector links, $l = (i, i') \in R$, that connect a centroid to the transportation network is 0.

$$\varphi_{i,i'}(X, Y) = 0$$

In order to calibrate the safety term in sidewalk cost function, we used crash data and traffic counts on Starkville, Mississippi, USA. For each street in Starkville we define a crash probability by dividing total number of crashes by total traffic flow on that street. Then by using a simple linear regression among all the streets, we calculate the crash probability function. Table 2 shows the statistical results for our regression model where the dependent variable is the crash probability and independent variable is the auto traffic flow. In the case studies below, the same probability function has been used for all of the networks.

Table 2 Statistical regression results for pedestrian crash probability function based on Starkville crash data

	Coefficients	*Standard Error*	*t Stat*	*P-value*	R Square
Intercept	1.72E-07	4.67E-08	3.689076	0.001821	0.6
X Variable	3.59E-10	7.71E-11	4.660415	0.000224	

In the next section we test the proposed algorithms to solve the problem for three sample transportation network problems. (See Rashidi et al., 2015, for more discussion)

CASE STUDIES

To show the capability of the algorithm, the user equilibrium problem with network reconstruction has been formulated and solved for three networks: A small hypothetical network, the Hearn network (Hearn & Ramana, 1998) and Sioux Falls network. The specification of these networks (number of nodes, arcs and OD pairs) is given in Table 3. In all the case studies, several important assumptions are made:

- Travel demand is based on the number of passengers. There are three different passenger types: auto passengers, bus passengers and pedestrians. We also assume that each bus carries 20 passengers, making each bus is equivalent to 4 autos (Aashtiani, 1979).
- We assume that, on average, the pedestrian free flow time is five times the auto free flow travel time (Carey, 2005).
- For each of the origin-destination zones, a dummy node was added to the network. These dummy nodes are connected to their nearest sidewalk node with a connector arc which means passengers start and end their trips from sidewalks.
- Travel time is zero on connector arcs and it is a constant value on transfer arcs.
- Transportation demand and road capacity are known with certainty.
- The transit schedule is not explicitly modeled in our formulation. We assume that there are enough transits available at each station, and the passengers will not choose the auto mode over the transit mode because of the transit schedule.
- An out of pocket cost of $20 per hour is considered for auto links in order to make it competitive with pedestrian and transit links (we assume the auto links are similar in terms of link length, speed limit and number of lane, and out of pocket cost is equal

among all of them).

- The parameters used in the travel cost functions are as follows: $\alpha_1 = 0.15$, $\alpha_2 = 2$, $\beta_1 = 4$, $\beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 2$.

Table 3 Transportation networks specifications

Network	Number of OD pairs	Original network		Reconstructed Network	
		Number of nodes	Number of arcs	Number of nodes	Number of arcs
Small	4	4	5	21	65
Hearn	4	9	18	55	192
Sioux Falls	552	24	76	143	523

First, we exercise our model on the small network. Figure 3(a) shows the original small network with 4 nodes, 5 arcs and 4 OD pairs. After reconstructing the network, the number of its nodes and arcs increases to 21 and 65 respectively (Figure 3b). The traffic demand between OD pairs is given in Table 4.

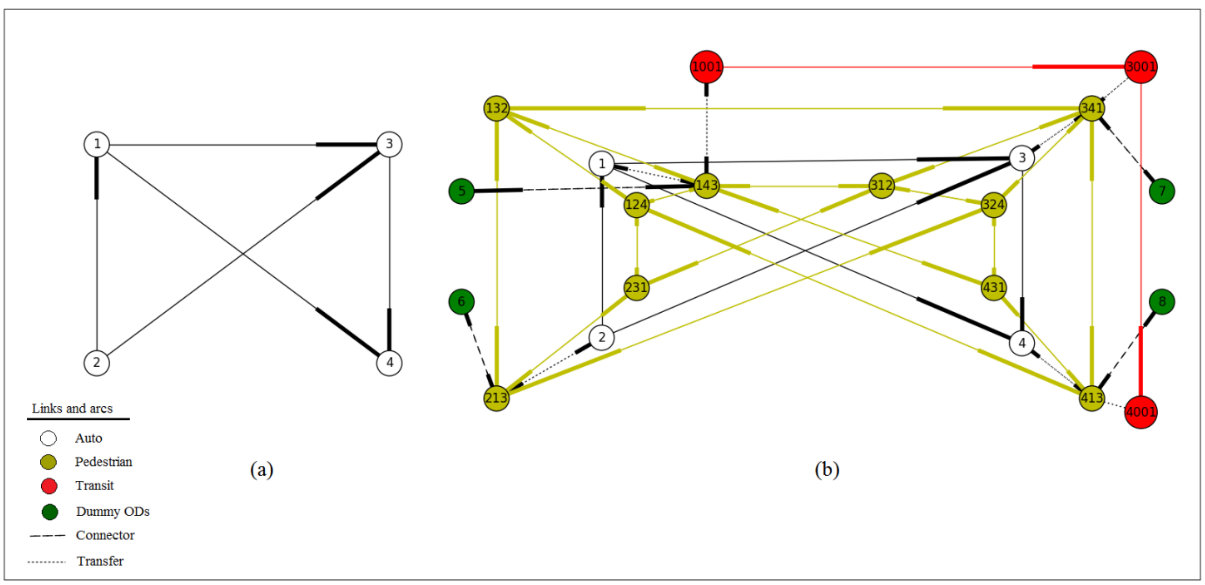


Figure 3 Small network, (a) original network (b) network after reconstruction

Table 4 Traffic demand for small network

OD	Demand

From	to	
5	7	10
5	8	40
6	7	20
6	8	60

In the next section we discuss the results of the experiments with the three sample networks.

DISCUSSION OF RESULTS

The problem was modeled in YALMIP (Lofberg, 2004), a toolbox for modeling and optimization in MATLAB, and the BARON (Sahinidis, 2014) solver, a computational system for solving mixed integer nonlinear programming problems, was used to solve the problem, but, even for the smallest sample network, the solver was incapable of solving the problem in a reasonable time. To solve the problem for large instances, we also developed a greedy heuristic (GH), and a simulated annealing (SA). The results show that the GH and the SA can produce competitive solutions and their solutions show a decrease in the overall cost of the transportation networks after optimally implementing sidewalks and crosswalks. We also ran a set of experiments considering a limit on the budget for implementing traffic calming actions and test the GH and SA performance. The results show that as the budget increases and therefore more traffic calming is implemented, the overall cost decreases in all three networks. However the rate of decrease diminishes as the budget increases, as shown in Figure 4**.** For the hypothetical small network and the Hearn network, there is no significant difference between the solution quality produced by GH and SA; however, for the Sioux Falls network the SA outperforms the GH for lower budget, but as the budget increases, the difference between the two algorithms diminish such that for higher budget there is no significant difference between the solutions that the two algorithms generate.

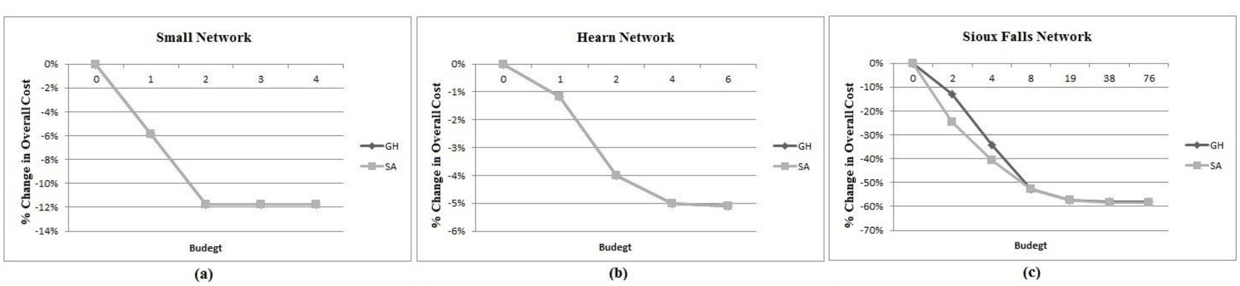


Figure 4 Percentage changes in overall costs for different budget

Even though implementing sidewalks and crosswalks decreases the overal cost in transportation networks, it has a different impact on different modes of transportation. Considering the importance of safety for pedestrians, as expected, implementing traffic calming causes higher decrease in pedestrian travel cost than in transit and auto cost, as shown in Figure 5**.**

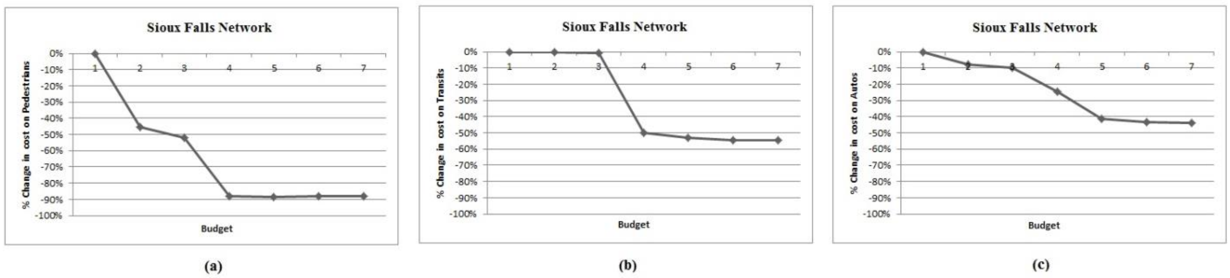


Figure 5 Percentage change in cost over different transportation mode

Considering the computation time, for the hypothetical Small network and Hearn network, the GH is faster than the SA. This is likely because the small size of these networks. However, for the largest network, the Sioux Falls, as the budget increases, the GH becomes computationally more expensive than SA, as shown in Figure 6**.** In conclusion, for the larger Sioux Falls transportation network, the SA outperforms GA in solution quality and computation time.

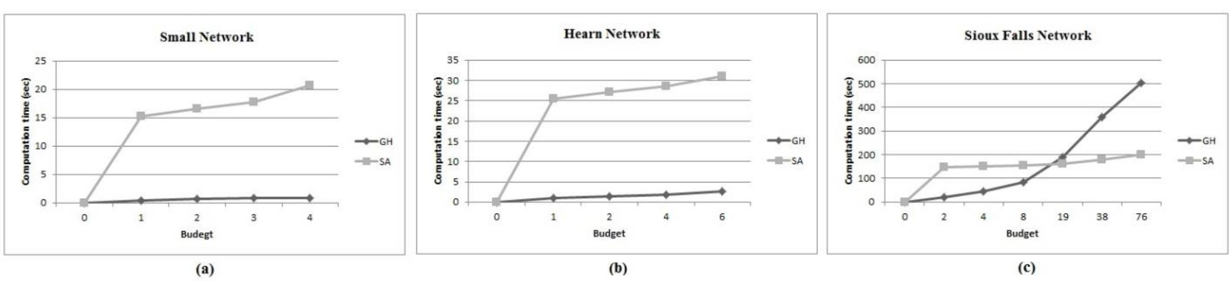


Figure 6 Computation time, GH v.s. SA for the three sample networks

To investigate the impact of traffic calming under different traffic congestion scenarios, we have evaluated the percent change in overall cost over the changes in demand as shown in Figure 7**.** When the networks are less crowded, implementing traffic calming did not have a significant impact in the overall traffic cost. However, as the demand increases and more people use the network, traffic calming starts to have more significant effect. This effect continues until a certain point where the network becomes overcrowded and the effect of traffic calming starts to diminish.

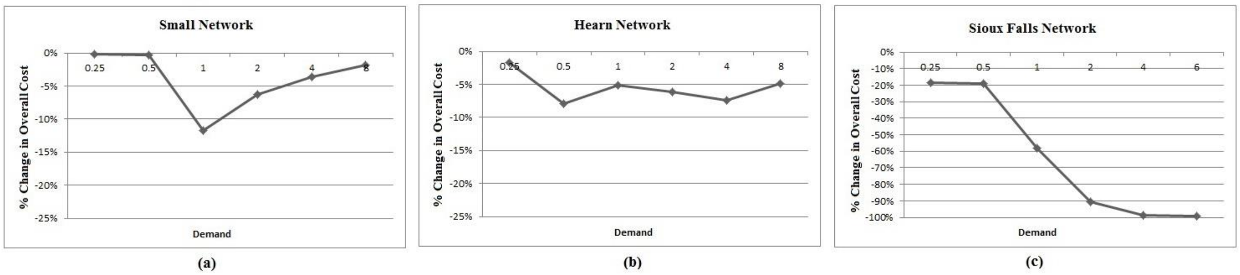


Figure 7 Percent change in overall cost due to traffic calming for various demand

To further study the impact of safety on the overall cost in the transportation networks, and to find a compromise between safety and time, we ran experiment with different safety weights, δ in the pedestrians cost function on sidewalk links, ranging from 0.0 to 1.0. As can be seen in Figure 8 for all ranges of the safety weight factor, implementing traffic calming decreases the overall cost.

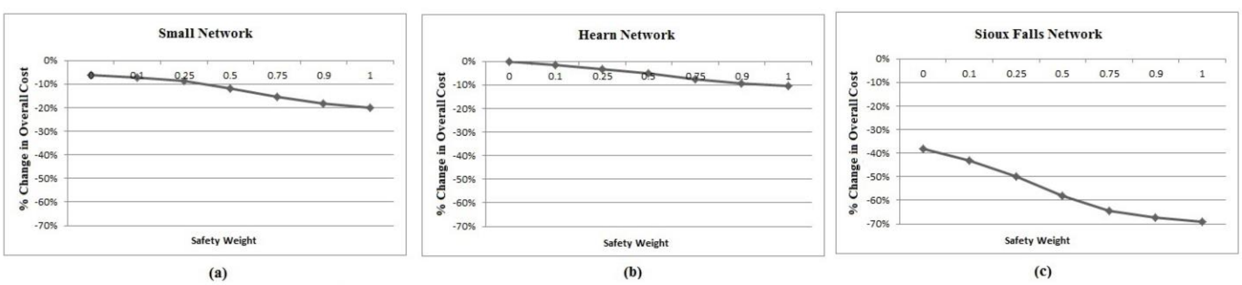


Figure 8 Percent change in overall cost considering different weight for safety and time

To see the impact of traffic calming, demand, and safety weight factor on the optimal flow solution, we depict the small network under different scenarios as shown in Figure 9. The graph in part 1.a. shows the flow in the network before implementing traffic calmings, and part 1.b. after implementing traffic calmings.

As can be seen from these graphs, the auto link (1,3) is no longer used after implementing traffic calmings, and on the other hand transit link (1001, 3001) is used. Also, some pedestrian links are used more after traffic calming, such as (2,324), (324, 431), and (431, 413). The transit link (3001, 4001) is used slightly less than before implementing calming.

Figure 7.2.a and 7.2.b. show the difference in the flow in the Small transportation network under low and high traffic respectively. It appears that when the transportation network becomes congested, less auto link-modes are used and more pedestrians and transit link-modes are used.

Figures 7.3.a and 7.3.b. show the transportation network under low safety weight, $\delta = 0.1$, and high safety weight, $\delta = 0.9$. It seems that increasing the safety factor makes the pedestrian and some auto links be used more often and transit links less often. The auto link-modes (1, 3) and (2, 1) are used more often, as well as the pedestrian link-modes (124, 413), (143, 124), (132, 124), (324, 431), and (431, 413). On the other hand, transit links are used less often.

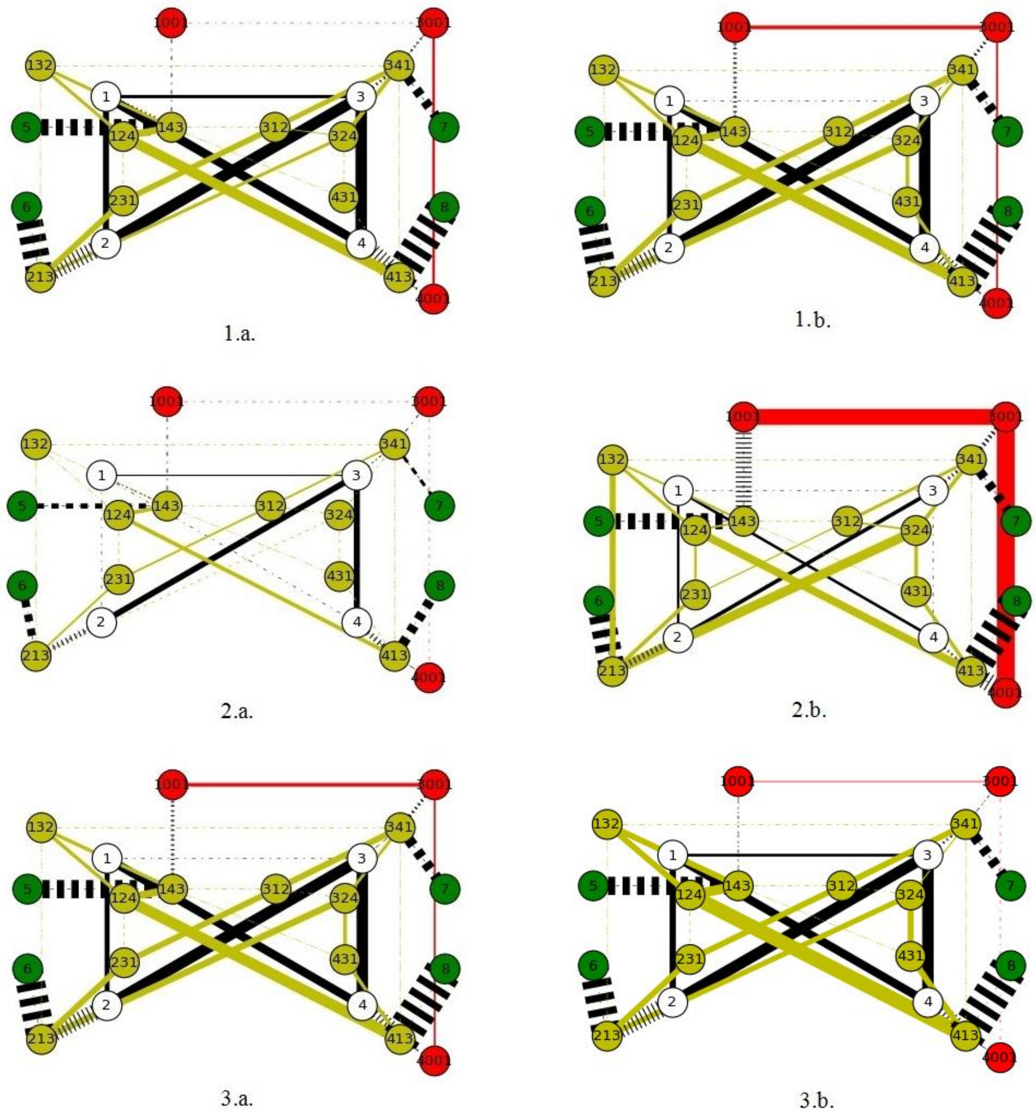


Figure 9 Small Transportation Network under different scenarios: 1. Before and after implementing calming, 2. For low and high crowd congestion, and 3. For low and high safety weight.

CONCLUSIONS

This study provides inside into how implementing traffic calming actions such as constructing sidewalks and crosswalks affect the overall transportation cost and traveler safety in a multimodal transportation network design problem. Our results indicate that these traffic calming actions reduces the overall cost of transportation and increases pedestrian safety increases. This reduction and increase is especially significant as the size of transportation network problem grows. In addition, the results show that the decision of which traffic calming to implement and where to implement is most critical when the budget is small.

Interestingly, the results indicate that implementing sidewalks and crosswalks not only decreases the overall transportation cost, it also increases the number of pedestrians and reduces the number of auto users in the network. This result indicates that traffic calming can change pedestrian safety on roadways to the point in which users change their mode.

From a computational point-of-view, the results indicate that the BARON solver is incapable of solving even the smallest instances of our network design problem. On the other hand, the proposed greedy heuristic (GH) and simulated annealing algorithm (SA) are able to solve the problems and produce approximate solutions in reasonable time. However the SA produces better solutions than the GH and is also faster for the larger transportation network.

RECOMMENDATIONS AND FUTURE WORK

Implementing sidewalks and crosswalks appear to effectively decrease the overall transportation cost and increase safety for pedestrians traveling in a transportation network.

The only traffic calming actions considered in this paper are the construction of sidewalks and crosswalks. However, there are many more actions to consider such as speed bumps, stop lights, stop signs and police patrol. In addition, though the approximate methods proposed here work well, because of the bi-level nature of the problem, decomposition methods can be tried in solving the problem more accurately.

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