Optimizing Traffic Calming in a Multi-Modal Transportation Network

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Outline

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- Network Representation
- Mathematical Model
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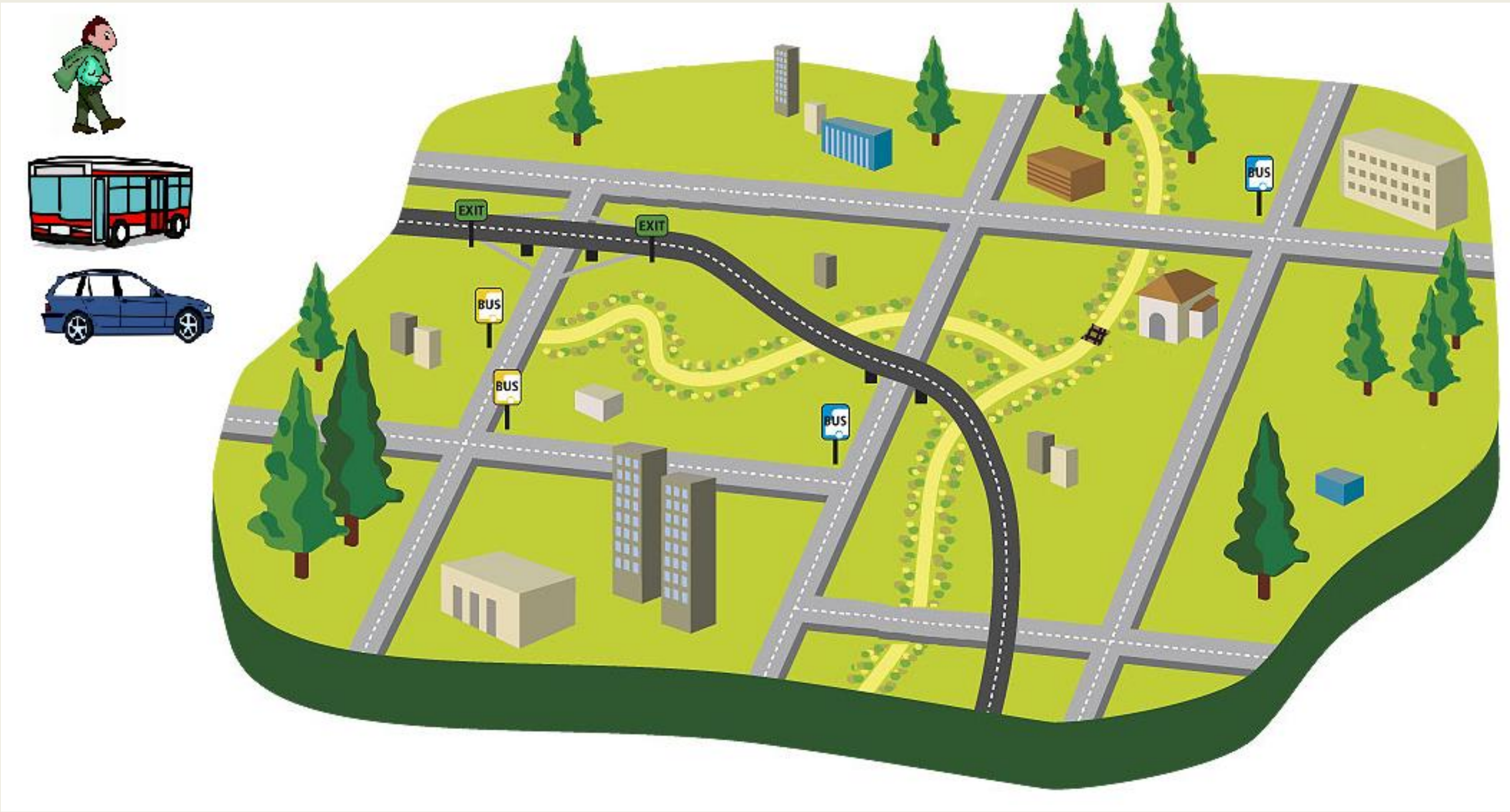
Motivation

- "In 2010, the Federal Highway Administration Estimated [1] that **4,500** pedestrians **annually** are killed 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"

Solution:

To help communities address this common lack of infrastructure, we propose a mathematical programming model for optimally locating sidewalks and crosswalks in a transportation network so that the pedestrians' safety increases and the total travel cost decreases.

Problem Description



Network Representation

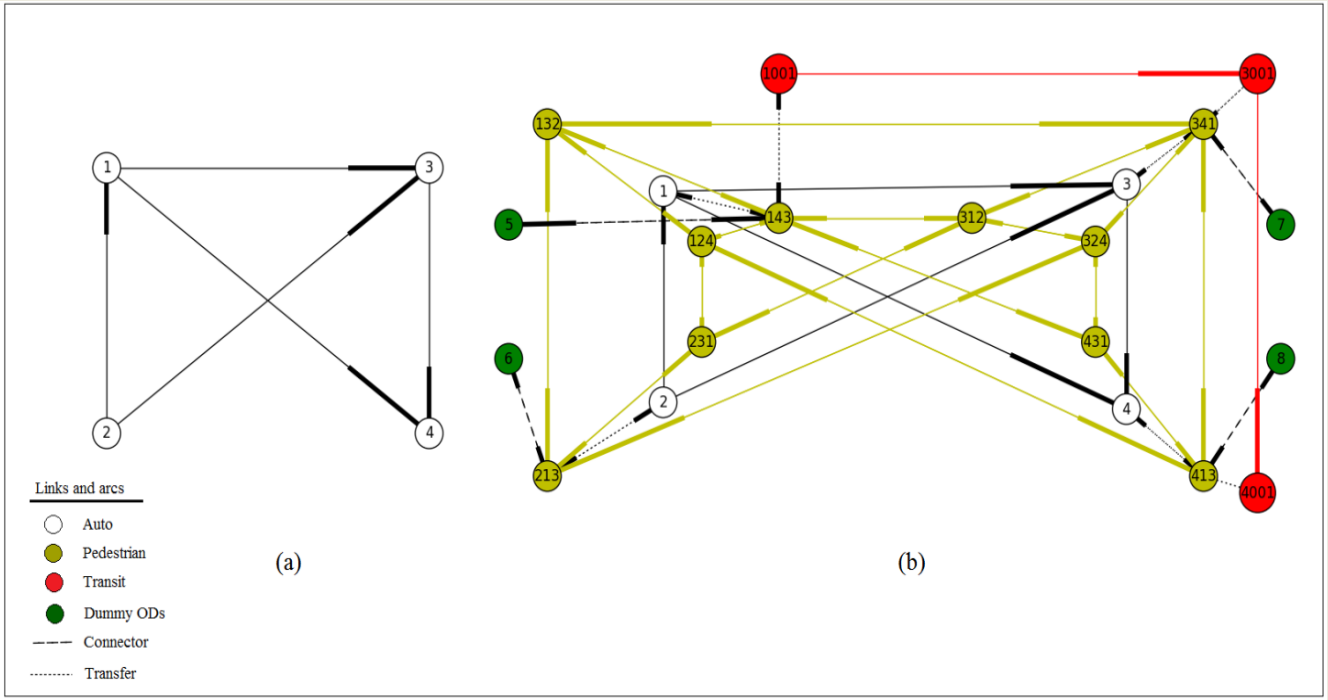


Fig1. Small network, (a) original network (b) network after reconstruction

Notations

- $\boldsymbol{X_{klm}}$**:** Amount of trip k flows on mode-link (l, m)
- $\boldsymbol{Y_{jla}}$**:** Binary variable, **1** if traffic calming facility j is implemented on auto link la, **0** otherwise
- $\boldsymbol{\pi_{ik}}$**:** Auxiliary variable, the dual variable of the corresponding shortest path problem
- $\boldsymbol{\delta}$: Safety weight factor
- $\boldsymbol{\varphi'_{lm}(.)}$**:** Travel cost function in the <u>upper level</u> for mode-link (l, m)
- $\boldsymbol{\varphi_{lm}(.)}$**:** Travel cost function in the <u>lower level</u> for mode-link (l, m)

Mathematical Model

$$Min \quad \sum_{k\in K}\sum_{(i,i')\in L} \acute{\varphi}_{(i,i')}(X,Y)X_{k,(i,i')} \qquad (1)$$

$s.t.$

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

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

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

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

$$X_{k,(i,i')} \geq 0 \quad \forall k\epsilon K, (i,i')\epsilon L \qquad (6)$$

$$\pi_{ik} \geq 0 \quad \forall k\epsilon K, i\epsilon I \qquad (7)$$

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

Total travel cost (1)

User Equilibrium (2)

Demand (Supply) (3)

Flow Conservation (4)

Installment Budget (5)

Variable Range (6), (7), (8)

Travel Cost Function

Different Travel Cost Function for different mode-link:

$$l = (i, i') \in A$$

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

$$\times \left(\left(\left(\left(\frac{\sum_{k\in K} X_{ks1pla}}{\gamma_{l'p}} \right)^{\beta_1} + \left(\frac{\sum_{k\in K} X_{ks2pla}}{\gamma_{l'p}} \right)^{\beta_1} \right) \times (1 - y_{s,la}) \qquad (i)$$

$$+ \left(\frac{\sum_{k\in K} X_{kl'bxla}}{\gamma_{l'c}} \right)^{\beta_2} \times (y_{bx,la}) + \left(\frac{\sum_{k\in K} X_{kl'exla}}{\gamma_{l'c}} \right)^{\beta_2} \times (y_{ex,la}) \qquad (ii)$$

$$+ \ t_{la} \left(1 + \alpha_1 \left(\frac{\sum_{k\in K} X_{kla} + \sum_{k\in K} \omega X_{kl'tla}}{\gamma_{la}} \right)^{\beta_3} \right) \right) + \mu_{la} \qquad (iii)$$

Sidewalk part

Crosswalk part

Auto and Transit part

Travel Cost Function

Transit:

$$l = (i, i') \in T$$

$$\varphi_{(i,i')}(X,Y) = \vartheta \times t_{la}\left(1 + \alpha_2\left(\frac{\sum_{k\epsilon K}(X_{k,lt} + \theta X_{klalt})}{\gamma_{l,t}}\right)^{\beta_4}\right)$$

Travel Cost Function

Side Walk:

$$l = (\mathrm{i}, \mathrm{i}') \in S$$

Travel cost function in the **Lower Level**

$$\varphi_{(i,i')}(X,Y) = \vartheta\left(t_{lp} + \propto_3 \left(\frac{X_{lp}}{\gamma_{lp}}\right)^{\beta_5}\right) + \vartheta\left(\frac{\sigma P_{la}(X_{l'alp})X_{l'alp}}{0.01 \times \gamma_{lp}}\right)$$

Safety weight factor

$$\acute{\varphi}_{(i,i')}(X,Y) = \vartheta\left((1-\delta)\left(t_{lp} + \propto_3 \left(\frac{X_{lp}}{\gamma_{lp}}\right)^{\beta_5}\right) + \delta\left(1 - y_{s,lp}\right)\frac{\sigma P_{la}(X_{l'alp})X_{l'alp}}{0.01 \times \gamma_{lp}}\right)$$

Travel cost function in the **Upper Level**

Travel Cost Function

Crosswalk, Transfer, and Connector links:

Crosswalk

$$l = (i, i') \in C$$

$$\varphi_{(i,i')}(X,Y) = \vartheta \left(t_{l,s} + \propto_4 \left(\frac{X_{lp}}{\gamma_{lp}}\right)^{\beta_6} \right)$$

Transit Transfer

$$l = (i, i') \in F$$

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

Connector

$$l = (i, i') \in R$$

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

Methodology

BARON Solver

BARON is a computational system for solving **nonconvex** optimization problems to global optimality. Purely continuous, purely integer, and mixed-integer nonlinear problems can be solved with the software [2].

Greedy Heuristic (GH)

- A **Greedy Heuristic** is an algorithm that follows the problem solving heuristic of making the locally optimal choice at each stage with the hope of finding a global optimum [3].

Simulated Annealing (SA)

- The **SA** is a generic probabilistic metaheuristic for the global optimization problem of locating a good approximation to the global optimum of a given function in a large search space.
- The name and inspiration come from annealing in metallurgy.
- The notion of cooling schedule is implemented in the SA algorithm as a (slow) decrease in the probability of accepting worse solutions as it explores the solution space [4].

Table 1. SA parameters and their values

Parameter	Value
$Temp_{max}$	42000
$Temp_{min}$	0.00001
$Iter_{max}$	20
$\propto$	0.80

Numerical Experiments

Input Data

Table 3. Sample Transportation Networks

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

Table 4. Demand for different OD pairs for the Small and Hearn Networks

Small Network			Hearn Network		
OD Pairs		Demand	OD Pairs		Demand
from	to		from	to	
5	7	10	10	12	20
5	8	40	10	13	40
6	7	20	11	12	60
6	8	60	11	13	80

Computational Comparisons

Table 5. Computational Comparisons

Network	$ Cost before traffic calming	$ Cost after traffic calming	% of reduction in cost
Small	1480	1306	12
Hearn	3236	3071	5
Sioux Falls	12075400	5003300	59

The Effect of Budget

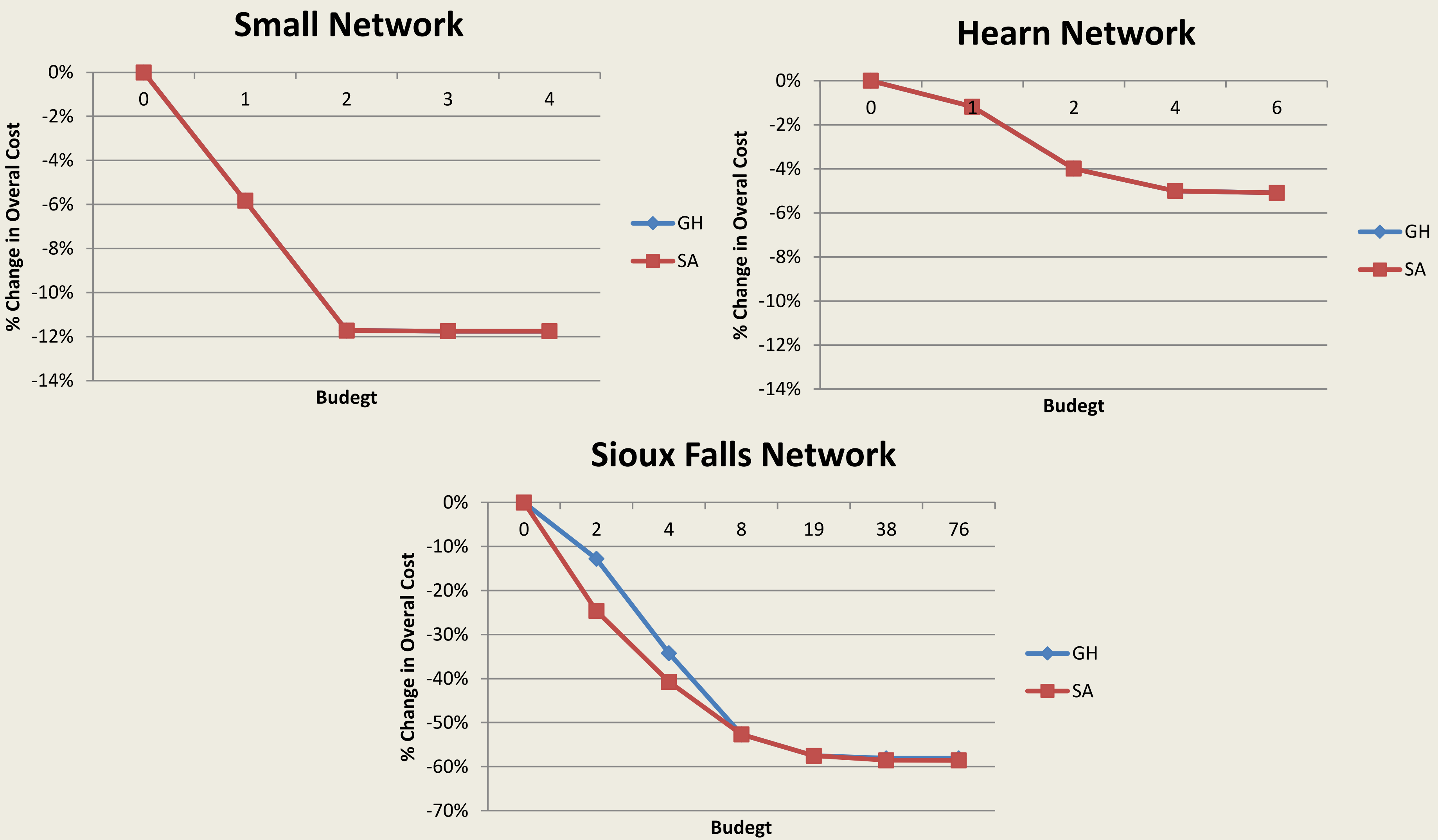
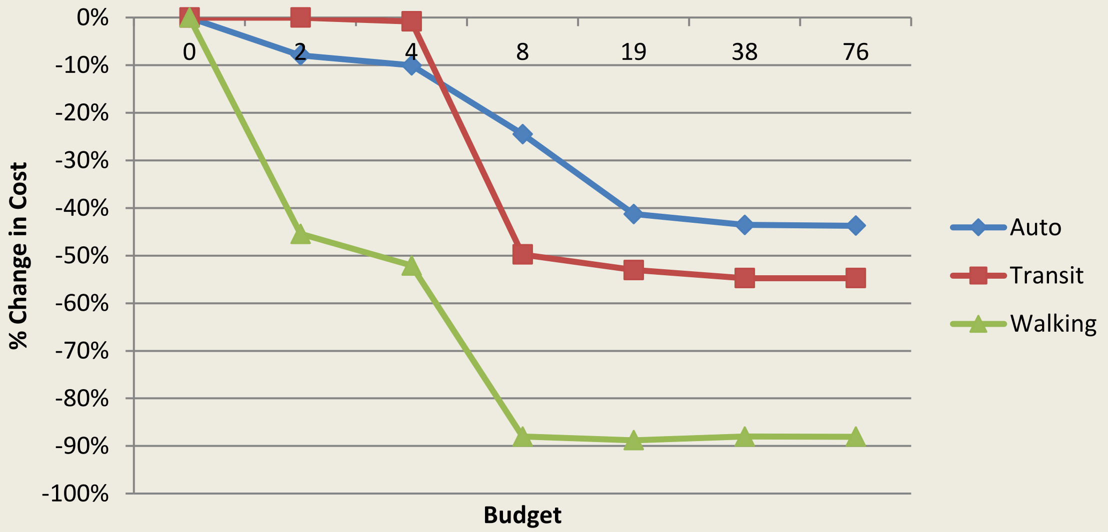


Fig 3. Percent Change in overall costs for different budget

The Effect of Traffic Calming Methods on Different Modes



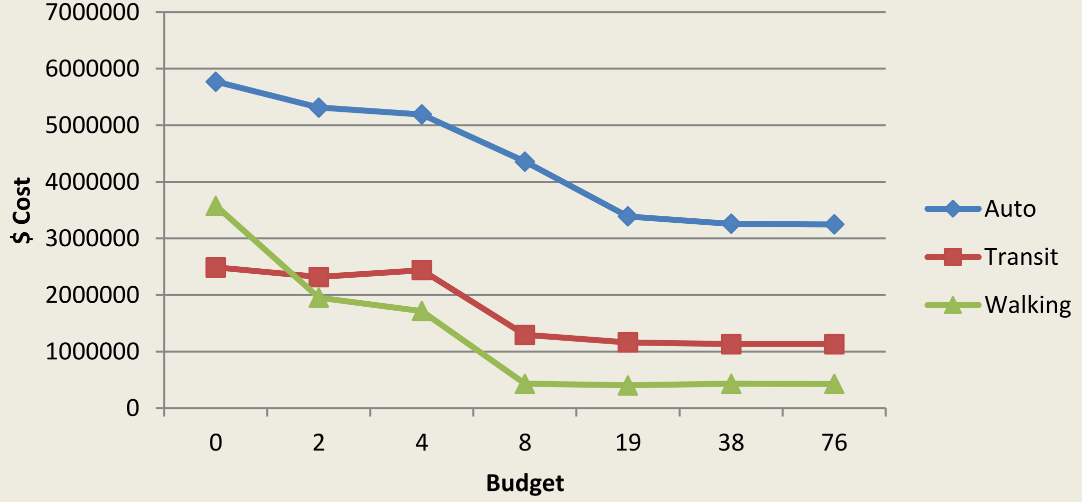


Fig 4. Percentage change in cost over different transportation mode for the Sioux Falls network

Computation Time: A Comparison

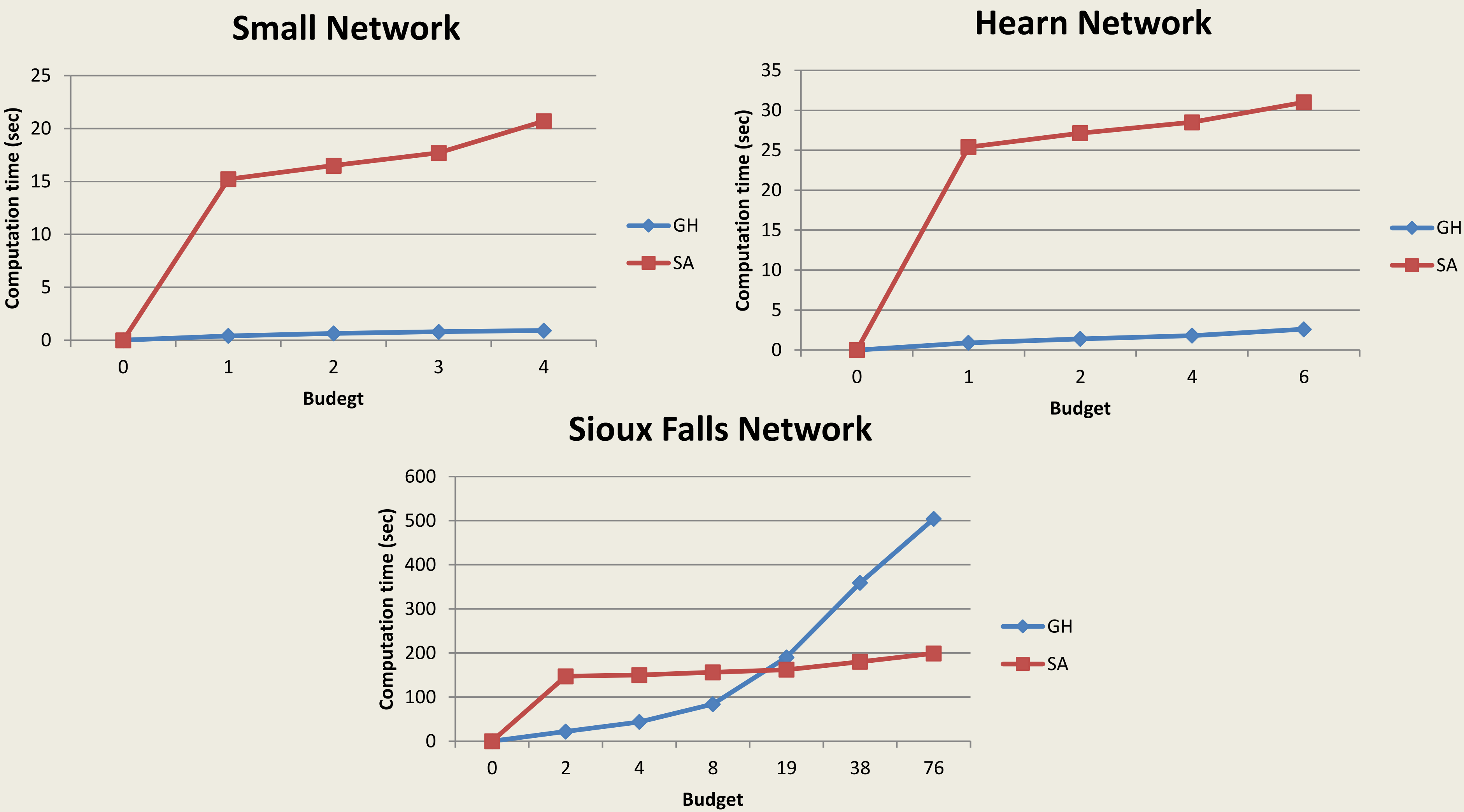


Fig 5. Computation time, GH v.s. SA for (a) Small Network, (b) Hearn Network and (c) Sioux Falls

The Effect of Safety Weight Factor

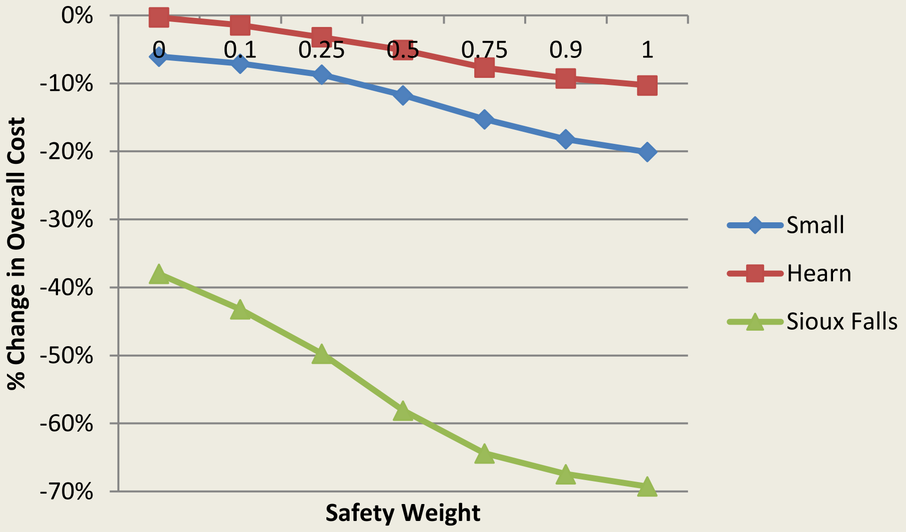


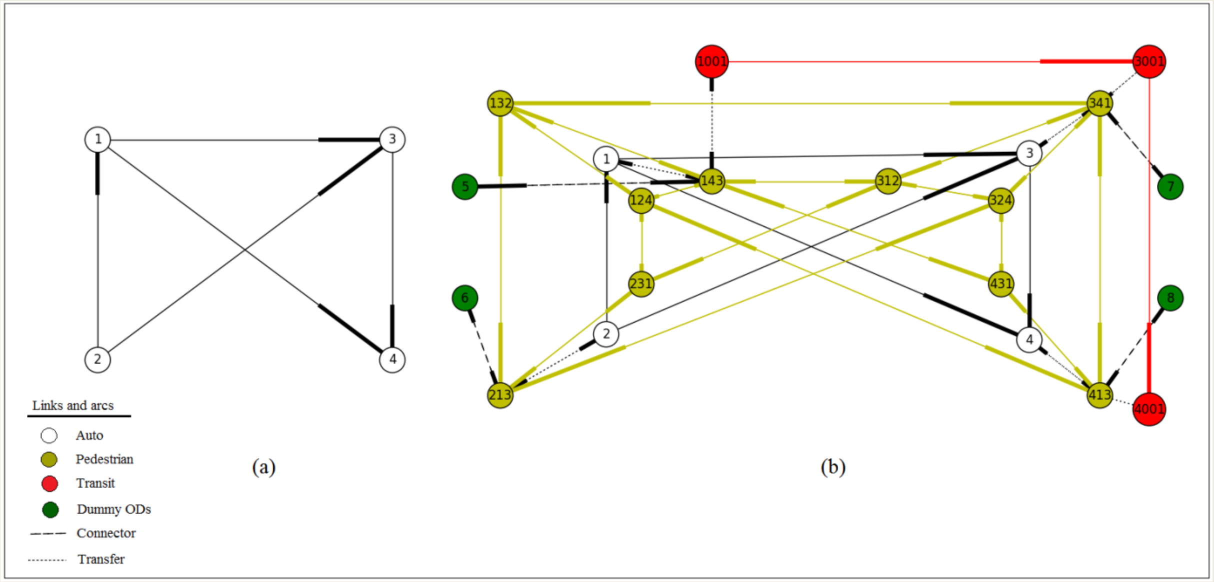
Fig 6. Percent change in overall cost considering different weight for safety and time

Case Study

Traffic Flow in the Small Network

Case Study

Review Network Representation



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Case Study

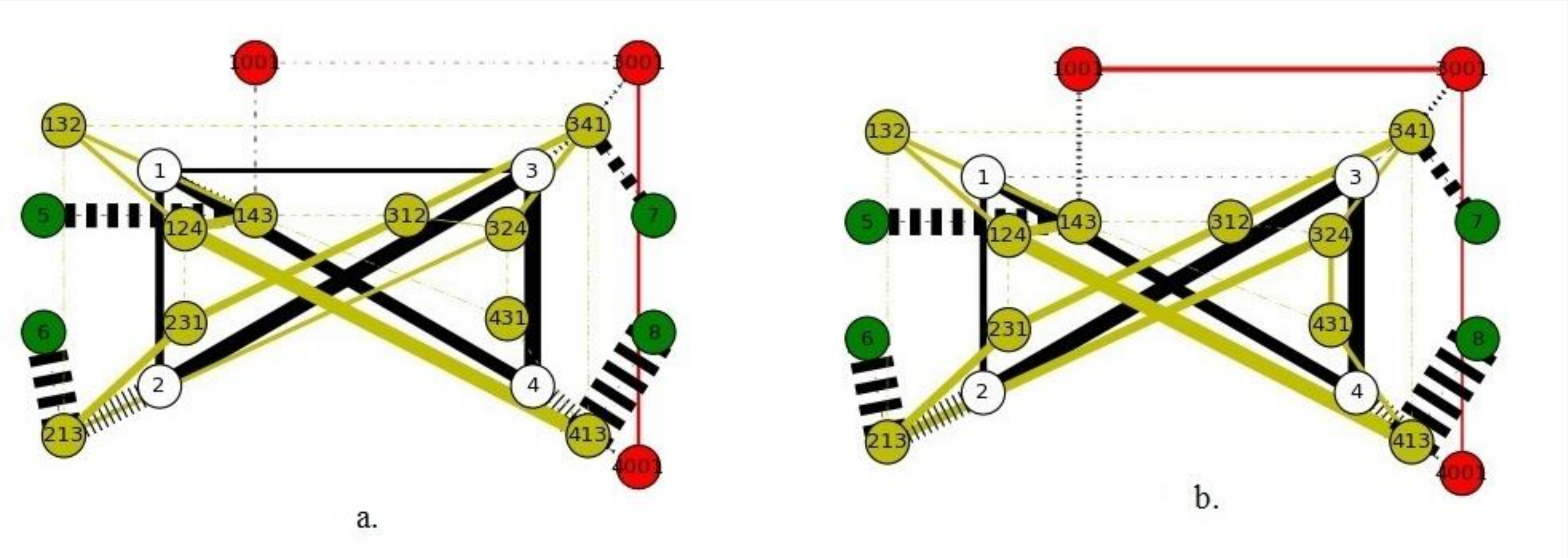


Fig 7. Traffic flow in the Small network, (a) Before implementing Traffic Calming
(b) After implementing Traffic Calming

Case Study

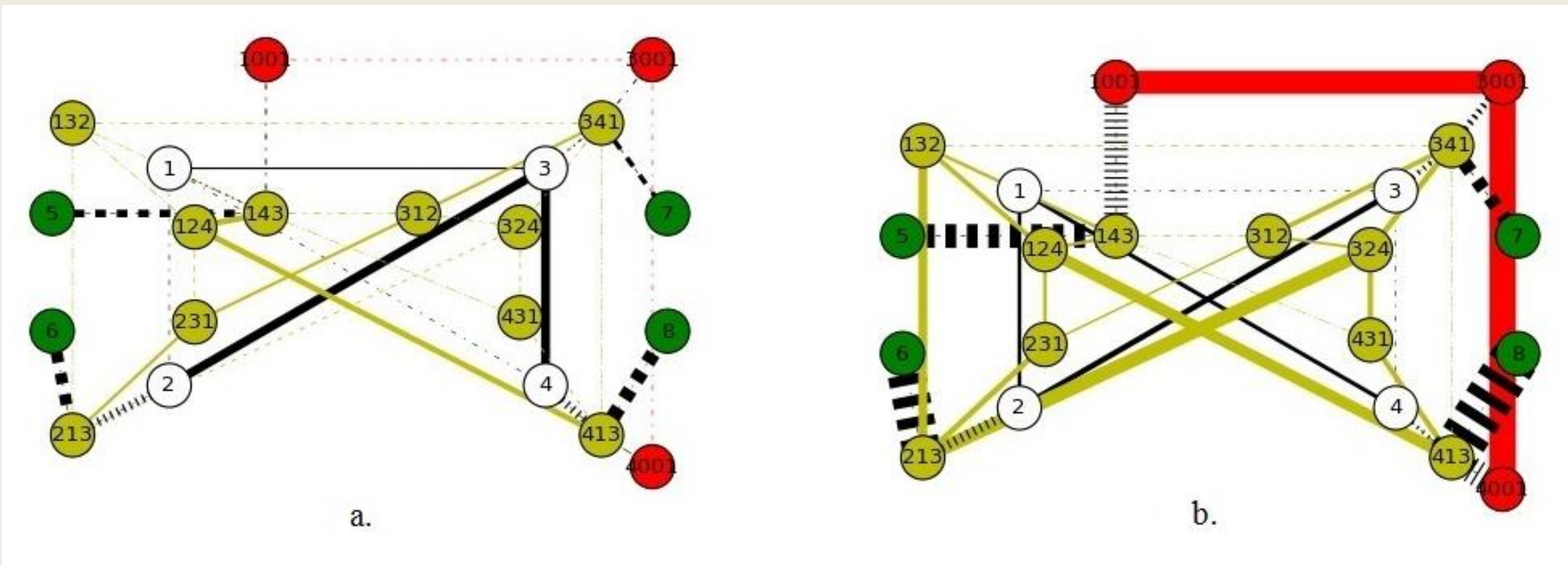


Fig 8. Traffic flow in the Small network after installing traffic calming measures
(a) Low traffic demand
(b) High traffic demand

Case Study

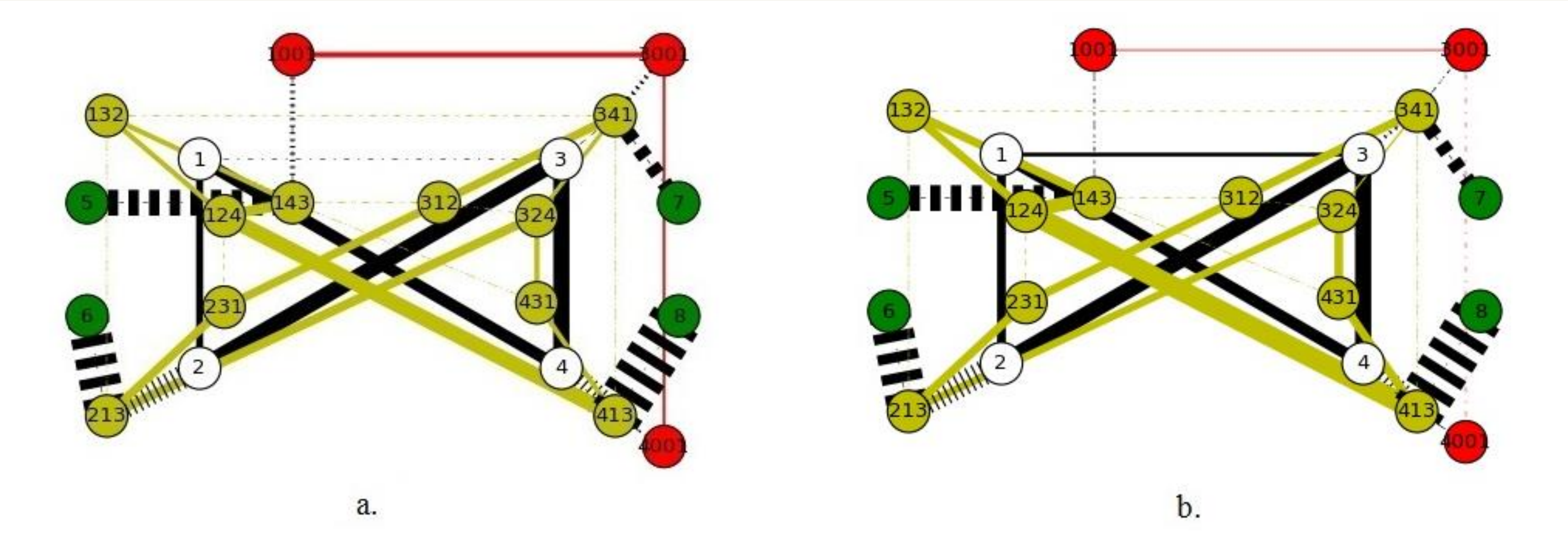


Fig 9. Traffic flow in the Small network after installing traffic calming measures
(a) Low safety weight
(b) High safety weight

Summary

- We propose a bi-level mixed integer programming model for optimally locating sidewalks and crosswalks considering the limited budget.

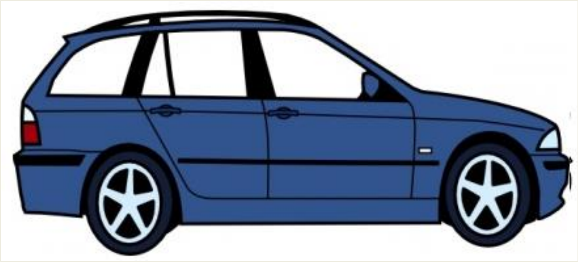
- Three sample networks are used for experimenting on the effect of installing sidewalks and crosswalks on the traffic flow, pedestrian's safety and total travel cost.

- We applied customized GH and SA to solve the problem. The BARON solver was also used to solve the problem.

Summary

- The SA algorithm shows to be faster and produces solutions with better quality for the larger network.
- The experiments show that installing sidewalks and crosswalks are effective in increasing pedestrians safety and decreasing the total traffic cost.

Questions?



References

[1] *Program, F. H. W. A. S. (2010) Safety benefits of walkways, sidewalks, and paved shoulders. Technical report, U.S. Dept. of Transportation, Federal Highway Administration, Office of Safety, Washington, D.C.*

[2] Tawarmalani, M. and N. V. Sahinidis, A polyhedral branch-and-cut approach to global optimization, Mathematical Programming, 103(2), 225-249, 2005.

[3] Retrieved from http://en.wikipedia.org/wiki/Greedy_algorithm

[4] Retrieved from http://en.wikipedia.org/wiki/Simulated_annealing