Coordinated Emergency Evacuation

Heng-Soon Gan[1] Mingzheng Shi[2] Kai-Florian Richter[3] Stephan Winter[4]

[1]Department of Mathematics and Statistics, The University of Melbourne, Australia.
[2]Centre for Technology Infusion, La Trobe University, Australia
[3]Department of Geography, University of Zurich, Switzerland
[4]Department of Infrastructure Engineering, The University of Melbourne, Australia

21st June 2013

The AMSI worshop on Mathematics of Transportation Networks

Presentation Outline

NOTE:

- This is only a **preliminary** work.
- Stochastic elements not (yet) considered.
- Proof of concept of the methodology.

The Emergency Evacuation Problem

The scenario:

1. Disaster detected.
2. Region(s) at risk identified.
3. Evacuation order issued for the region(s) at risk.

Aim:

We would like to evacuate the region(s) at risk as fast as possible.

The Evacuation Scenario

1. Region receives evacuation order to start evacuating at time T.
2. Between now and time T, evacuees prepare for evacuation.
3. On or after time T, evacuation begins.

We further assume that the evacuation order is issued **sufficiently in advance**, so that road infrastructure in the region is not currently affected by the disaster.

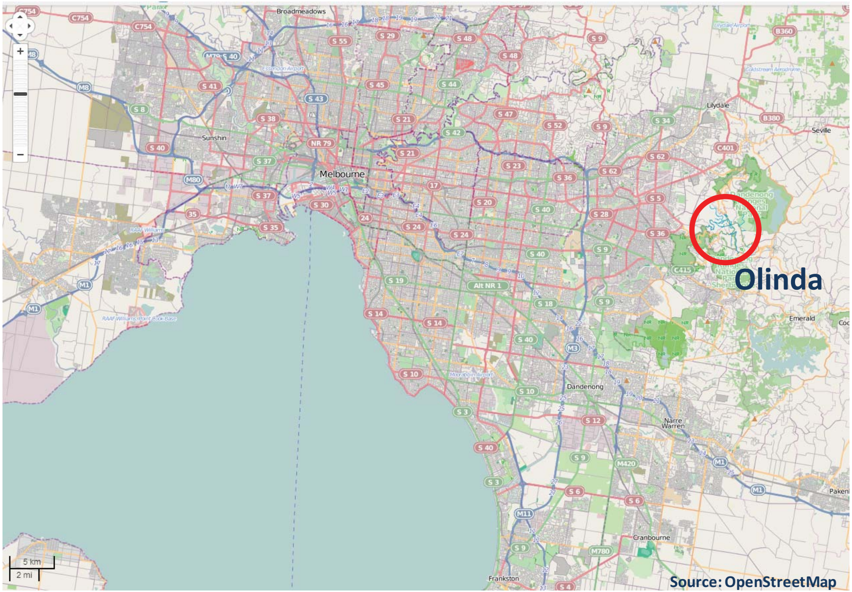
The Evacuation "Choice"

During the evacuation period:

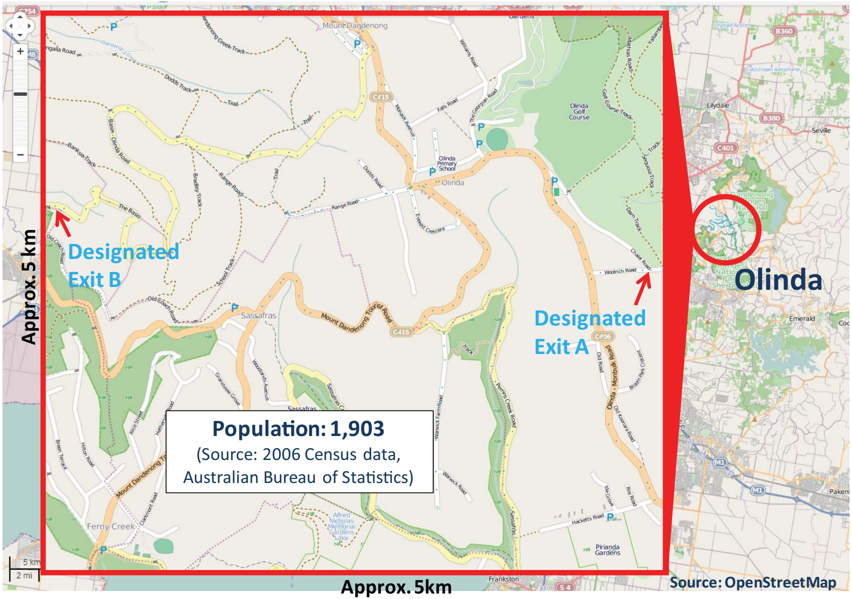
- All evacuees depart at time T.
- All evacuees are headed for their closest exit, via the shortest route (to the exit).

Is this a good idea?

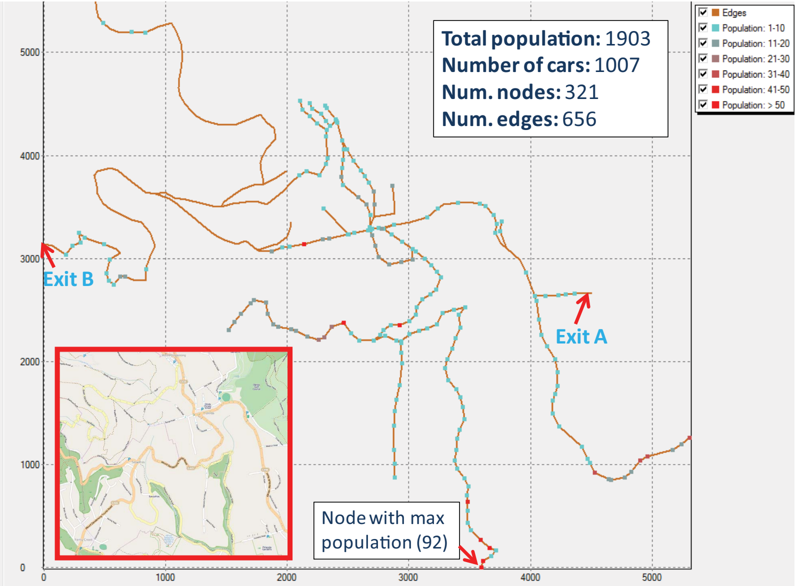
The Olinda Region (Dandenong Ranges)



The Olinda Region (Dandenong Ranges)



The Olinda Region (Dandenong Ranges)

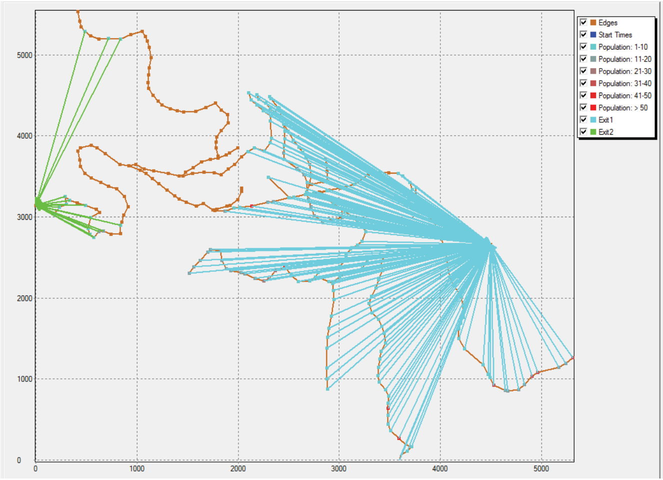


The DEFAULT case

Simulation:

- All evacuees depart at time $T = 0$.
- All evacuees are headed for their closest exit, via the shortest route (to the exit).
- No dynamic routing.
- Exits are uncapacitated.

The DEFAULT case - closest exits



	DEFAULT
Exit A	Total population: 937 # nodes: 224
Exit B	Total population: 70 # nodes: 97

iWays - A Microscopic Traffic Simulator

Developed by Rao Kotagiri, Lars Kulik and their students at the Department of Computing and Information Systems, The University of Melbourne.

- User interface.
- Incorporates Open Street Maps.

Based on the Intelligent Driver Model developed by Martin Treiber, Ansgar Hennecke and Dirk Helbing (Institute of Theoretical Physics, University of Stuttgart, Germany)

- A car-following model: acceleration/deceleration decisions depend on a car's own speed, its position, and the speed of the "leading vehicle" immediately ahead.
- The model solves a coupled ordinary differential equations in discrete time (speed, acceleration and vehicle gap).

iWays - Some key parameters

Minimum bumper-to-bumper distance to the front vehicle: **3 metres**

Desired safety time headway when following other vehicles: **1.5 seconds**

Desired speed when driving on a free road: **40 km/h**

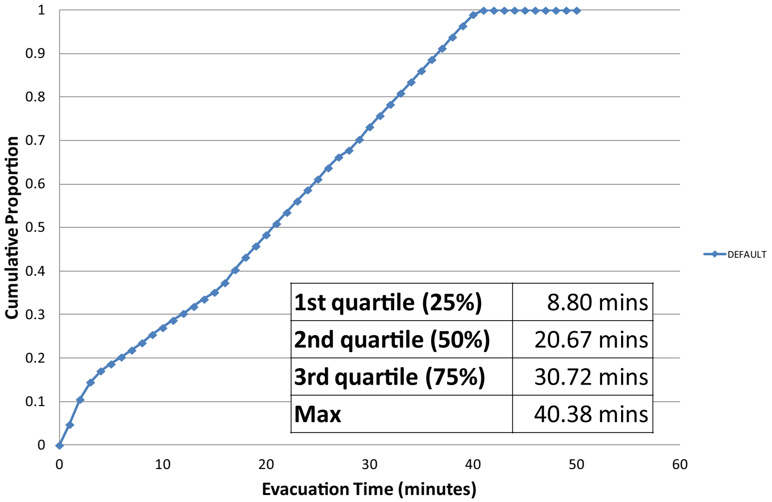
Acceleration in everyday traffic: **0.3 m/s**^{2}

Comfortable braking deceleration in everyday traffic: **3 m/s**^{2}

The DEFAULT case

(Show "DEFAULT" simulation)

The DEFAULT case



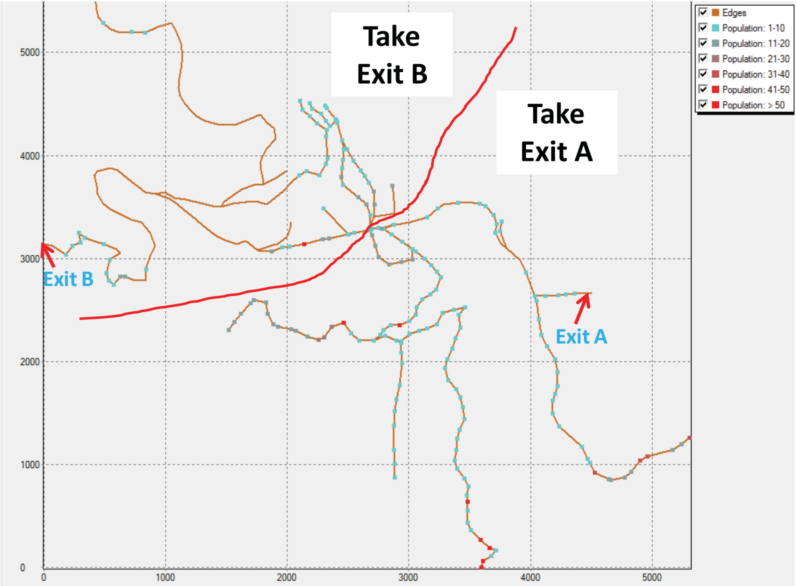
The DEFAULT case

Congestion is a problem (obviously).

How can congestions be managed *during evacuations*?

- **Planning phase** (staged evacuation/departure time coordination, exit assignment, route assignment)
- Realtime (e.g. control strategies)

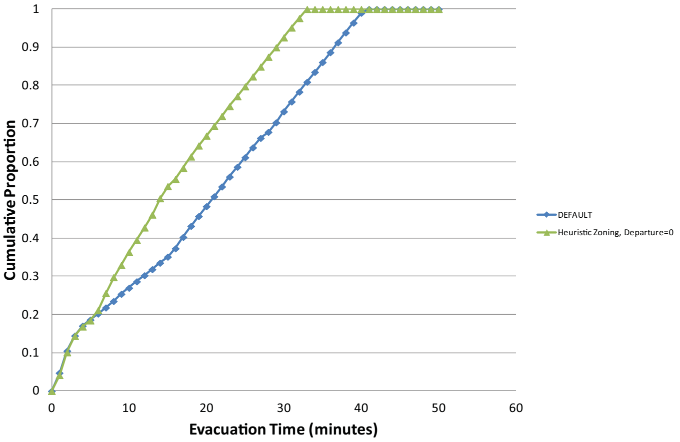
What about "Heuristic Zoning"?



Heuristic Zoning, Departure=0

	DEFAULT	Heuristic Zoning, Departure=0
1st quartile (25%)	8.80 mins	6.92 mins
2nd quartile (50%)	20.67 mins	13.93 mins
3rd quartile (75%)	30.72 mins	23.16 mins
Max	40.38 mins	32.95 mins

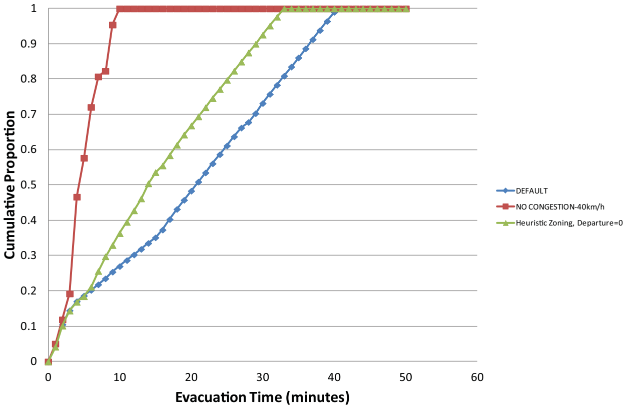
Improvement % over DEFAULT		
	DEFAULT	**Heuristic Zoning, Departure=0**
1st quartile (25%)	*	21%
2nd quartile (50%)	*	33%
3rd quartile (75%)	*	25%
Max	*	18%



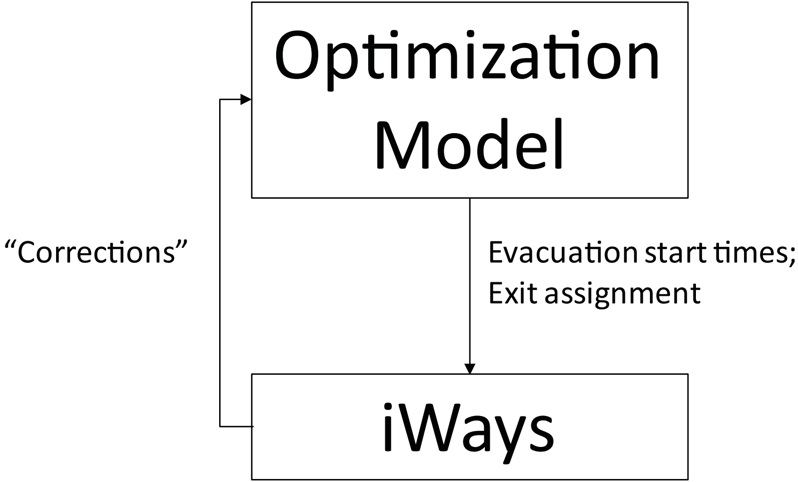
In the ideal world. . .

	DEFAULT	No congestion (40km/h)	Heuristic Zoning, Departure=0
1st quartile (25%)	8.80 mins	3.22 mins	6.92 mins
2nd quartile (50%)	20.67 mins	4.32 mins	13.93 mins
3rd quartile (75%)	30.72 mins	6.25 mins	23.16 mins
Max	40.38 mins	9.02 mins	32.95 mins

Improvement % over DEFAULT			
	DEFAULT	No congestion (40km/h)	Heuristic Zoning, Depature=0
1st quartile (25%)	*	63%	21%
2nd quartile (50%)	*	79%	33%
3rd quartile (75%)	*	80%	25%
Max	*	78%	18%



The Basic Idea



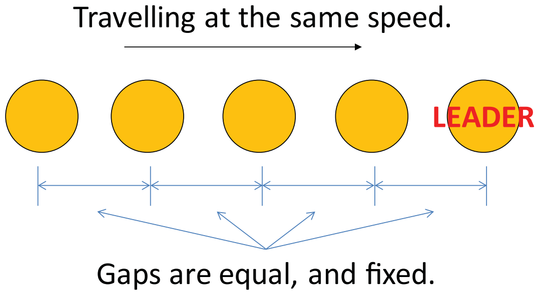
The Evacuation Coordination Problem

Aim: Given the set of nodes and their corresponding shortest routes to all exits, we wish to determine, *for each node with at least one evacuee*, its exit location and departure time, such that the *sum of all evacuation times* is minimized and arc capacity requirements are met.

NOTE: The "System Optimal Dynamic Traffic Assignment" problem is "demand driven" and allows for dynamic routing.

The Evacuation Coordination Problem - evacuees at the same location

For example, at a location with 5 evacuees,



The Evacuation Coordination Problem - Sets

We define the following sets:

$\mathbf{N}$, the set of all nodes;

$\mathbf{N}^E \subseteq \mathbf{N}$, the set of all nodes with at least one evacuee;

$\mathbf{A}$, the set of all arcs;

$\mathbf{E}$, the set of all exits;

$\mathbf{T} = \{1, 2, 3 \ldots\}$, the set of all time periods;

$\mathbf{T}^D = \{1, 2, 3, \ldots, T^{max}\} \subset \mathbf{T}$, the set of time periods when evacuees can depart.

The Evacuation Coordination Problem - Parameters

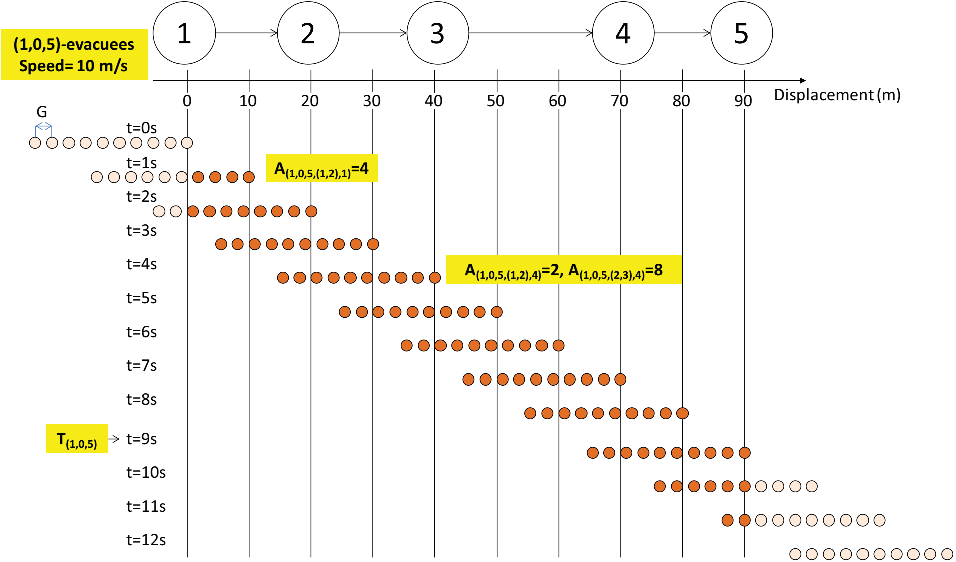
And the parameters for the model are:

Δ = size of one time period;
G = minimum bumper-to-bumper distance;
L_i = length of arc $i \in \mathbf{A}$;
$C_i = \left\lfloor \frac{L_i}{G} \right\rfloor$ capacity of arc $i \in \mathbf{A}$
P_w = population size at node $w \in \mathbf{N}^E$;

We will use the notation (w, t, e) to denote the evacuees, whose “leader” departs at time $t \in \mathbf{T}^D$ from their origin at node $w \in \mathbf{N}^E$ heading for the exit $e \in \mathbf{E}$ using the shortest route. The rest of the population follows the leader at a gap G.

V_{wte} = average speed of the (w, t, e)-evacuees;
T_{wte} = the time period when the *leader* of the (w, t, e)-evacuees arrives at exit $e \in \mathbf{E}$;
$A_{wtei\theta}$ = the number of (w, t, e)-evacuees on arc $i \in \mathbf{A}$ at time $\theta \in \mathbf{T}$;

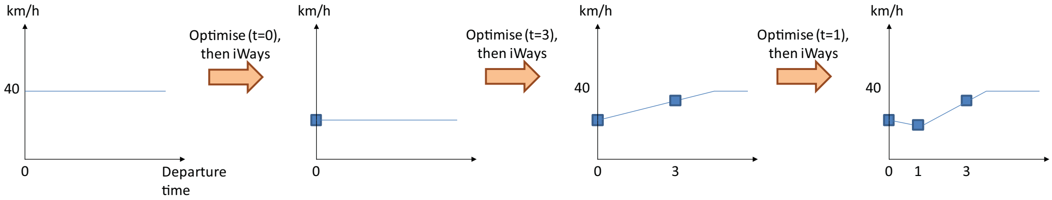
The Evacuation Coordination Problem - the parameter $A_{wtei\theta}$



The Evacuation Coordination Problem - the parameter V_{wte}

With updated information from the simulator (iWays), the average speed, V_{wte}, of (w, t, e)-evacuees is corrected in an iterative manner.

For each *w* and *e*,



The Evacuation Coordination Problem - decision variables

$$x_{wte} = \begin{cases} 1, & \textit{if the } (w, t, e) - \textit{evacuees are used}; \\ 0, & \textit{otherwise}. \end{cases}$$

for $w \in \mathbf{N}^E$, $t \in \mathbf{T}^D$ and $e \in \mathbf{E}$;

$a_{i\theta}$ = additional capacity on arc $i \in \mathbf{A}$ at time $\theta \in \mathbf{T}$.

The Evacuation Coordination Problem - problem formulation

$$\min \sum_{w \in \mathbf{N}^E} \sum_{t \in \mathbf{T}^D} \sum_{e \in \mathbf{E}} S_{wte} x_{wte} + \sum_{i \in \mathbf{A}} \sum_{\theta \in \mathbf{T}} \Pi_\theta a_{i\theta} \quad (1)$$

s.t.

$$\sum_{t \in \mathbf{T}^D} \sum_{e \in \mathbf{E}} x_{wte} = 1, \quad \forall w \in \mathbf{N}^E \quad (2)$$

$$\sum_{w \in \mathbf{N}^E} \sum_{t \in \mathbf{T}^D} \sum_{e \in \mathbf{E}} A_{wtei\theta} x_{wte} \leq C_i + a_{i\theta}, \quad \forall i \in \mathbf{A}, \theta \in \mathbf{T} \quad (3)$$

$$x_{wte} \in \{0, 1\}, \quad \forall w \in \mathbf{N}^E, t \in \mathbf{T}^D, e \in \mathbf{E} \quad (4)$$

$$a_{i\theta} \geq 0, \quad \forall i \in \mathbf{A}, \theta \in \mathbf{T} \quad (5)$$

The Evacuation Coordination Problem - problem formulation

. . . where,

$$S_{wte} = \frac{P_w}{2}\left(2(T_{wte} - 1)\Delta + \frac{(P_w - 1)G}{V_{wte}}\right)$$

and

$$\Pi_\theta = 250 - \frac{200}{(1.05)^{\theta-1}}$$

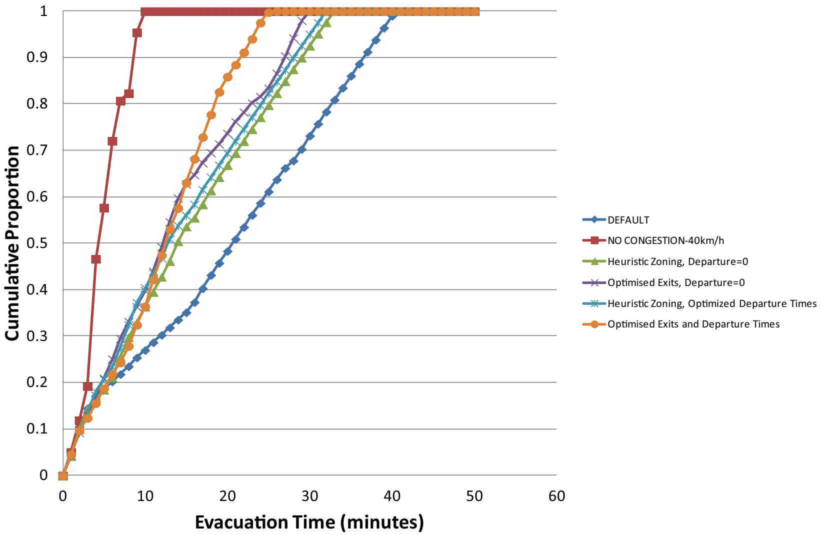
Other parameter settings:
$\Delta = 1$ minute
$G = 3$ metres
$\mathbf{T} = \{1, 2, 3, \ldots, 50\}$ (50 minutes)
$\mathbf{T}^D = \{1, 2, 3, \ldots, 11\}$ (first 10 minutes)

Optimized scenarios

- Heuristic zoning, optimized departure times;
- Optimized exits, departure=0;
- Optimized exits and departure times.

Optimised with FICO Xpress (Xpress Optimizer 23.01.03)

Optimized scenarios - results

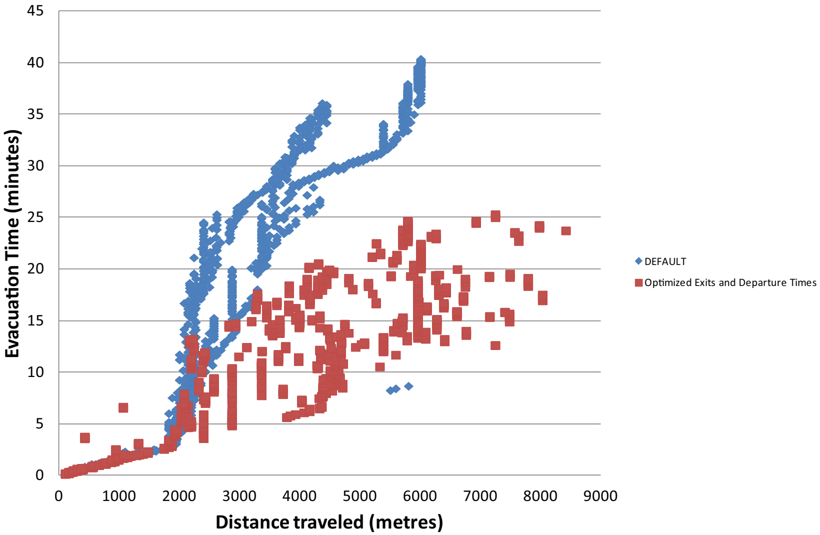


Optimized scenarios - results

	DEFAULT	No congestion (40km/h)	Heuristic Zoning, Departure=0	Heuristic Zoning, Optimized Departure Times	Optimized Exits, Departure=0	Optimized Exits and Depature Times
1st quartile (25%)	8.80 mins	3.22 mins	6.92 mins	6.41 mins	6.00 mins	7.24 mins
2nd quartile (50%)	20.67 mins	4.32 mins	13.93 mins	12.78 mins	12.17 mins	12.42 mins
3rd quartile (75%)	30.72 mins	6.25 mins	23.16 mins	22.19 mins	20.58 mins	17.46 mins
Max	40.38 mins	9.02 mins	32.95 mins	32.00 mins	29.8 mins	25.33 mins

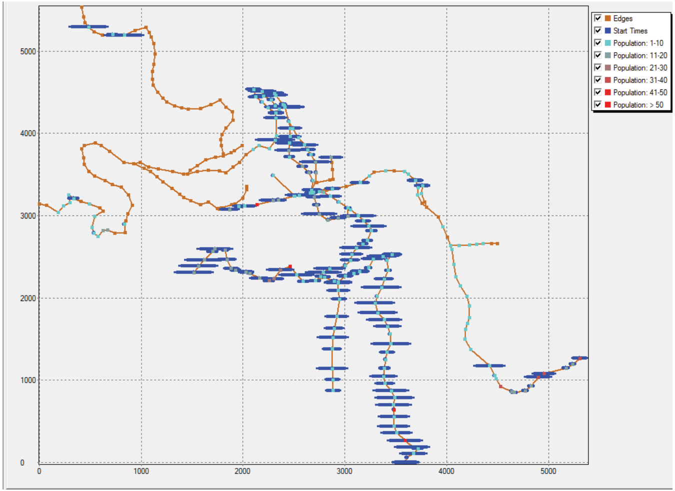
Improvement % over DEFAULT						
	DEFAULT	**No congestion (40km/h)**	**Heuristic Zoning, Depature=0**	**Heuristic Zoning, Optimized Departure Times**	**Optimized Exits, Departure=0**	**Optimized Exits and Depature Times**
1st quartile (25%)	*	63%	21%	27%	32%	18%
2nd quartile (50%)	*	79%	33%	38%	41%	39%
3rd quartile (75%)	*	80%	25%	28%	33%	43%
Max	*	78%	18%	21%	26%	37%

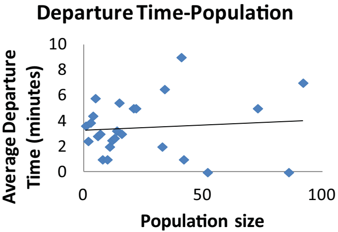
Optimized scenarios - results

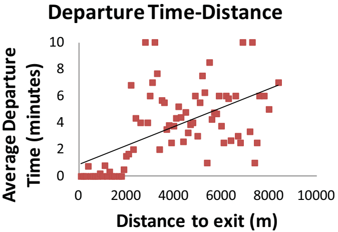


Optimized scenarios - departure times distributions

Optimized exits and departure times:

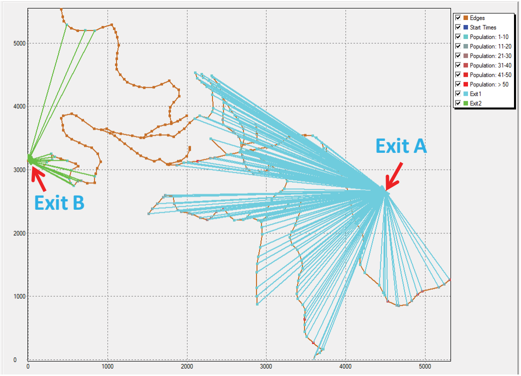




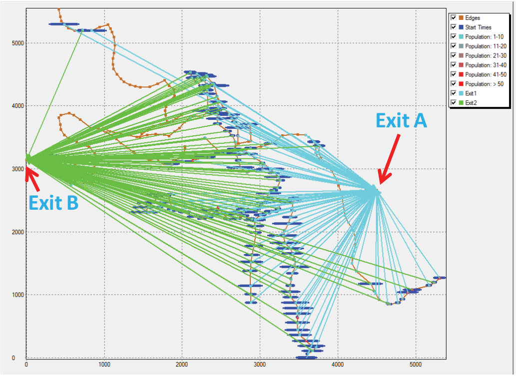


Optimized scenarios - exits

DEFAULT



Optimized exits and departure times



	DEFAULT	Optimized Exits and Departure Times
Exit A	Total population: 937 # nodes: 224	Total population: 609 # nodes: 128
Exit B	Total population: 70 # nodes: 97	Total population: 398 # nodes: 193

- An optimization-simulation framework introduced.
- With the appropriate "feedback" from the simulator, we may only be required to solve a simpler "surrogate" optimization problem. (c.f. solving the "system optimal dynamic traffic assignment" problem)
- The importance of staged evacuations and exit assignments in relieving congestions (re)emphasized. (consistent with the literature)
- Under ideal conditions, the optimized exits and departure times presents 37% improvement over the DEFAULT case, in terms of maximum evacuation time.

- Refine optimization-simulation framework;
- Verify repeatability of our method;
- Verify scalability of our method;
- Explore the "explainability" of the optimized solutions;
- Introduce stochastic events (e.g. disruptions) and ad-hoc response.

(Show "optimized exits and departure times" simulation)