Optimal street space allocation:

The installation of accelerated moving walkways to design a car-free city center

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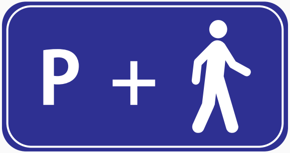
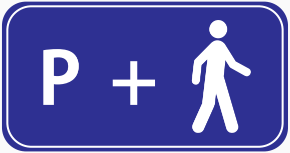
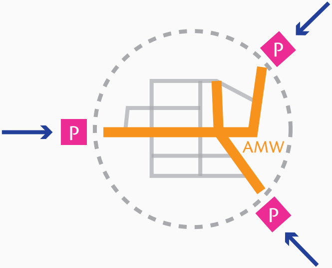
Motivation



Motivation





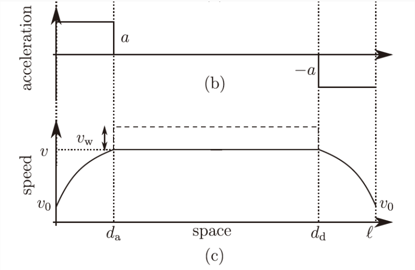
Network design with accelerated moving walkways (AMWs)

What's AMW?

Accelerated moving walkways:

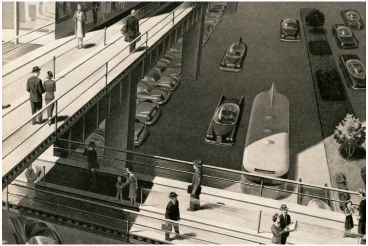
- Moving walkway with acceleration/deceleration parts
- Reaches the top speed of 15 - 17 [km/h]

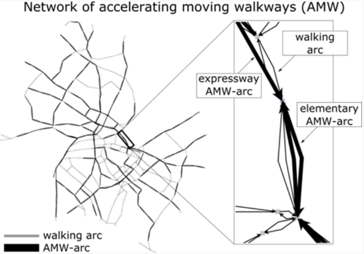
"Express Walkway" at the Tronto airport



AMW characteristics [1]

Install AMWs to city centers





Scarinci et al. (2017) [1]

A flexible public transport system:

- **High speed**: faster than vehicles during peak hours
- **Less operational constraints**: routing, stations and drivers
- **Low energy consumption**: one-third of electric buses
- **High capacity**: 4 times more using half space of private vehicles
- **Active mode**: a healthier life style

What's the problem?

Interaction with vehicles:

1. Capacity competition: $\kappa_{\text{veh}} + \kappa_{\text{ped}} = \text{constant}$.

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Interaction with vehicles:

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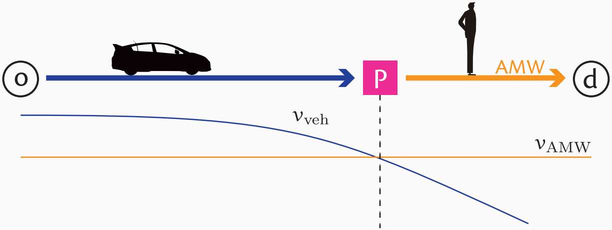
Question:

- The best strategy of traveler?



- Where to install, where will be congested?

Objectives

Find the optimal configuration of AMWs installation:

1. **Congestion of the mixed traffic**: a multi-layer network approach
2. With the **capacity competition**
3. Case study in a city center network

Network & Demand

Demand

Demand assumption:

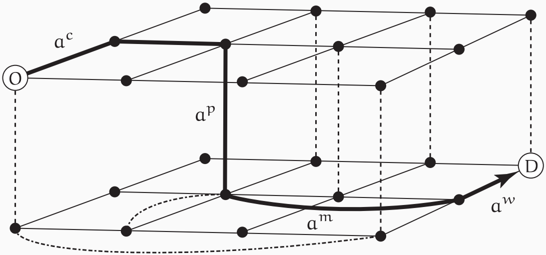
- N homogeneous car users
- Given OD demand
- Static congested network
- Minimizing travel time

Choice:

- **Parking place**
- **Driving route** to parking
- **Walking route** from parking to destination

A multi-layer network

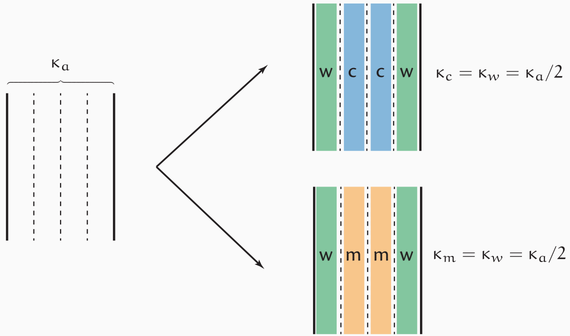
- $G = (N, A)$: graph of multi-layer network
- $N = N^c \cup N^w$: set of nodes (**car and walking layers**)
- $A = A^c \cup A^p \cup A^m \cup A^w$: set of links
- $O \subseteq N^c, D \subseteq N^w$: sets of origins and destinations



A multi-layer network

Layers interaction:

$$\kappa_a = \sum_{s \in \{c,p,m,w\}} \kappa_a^s \qquad (1)$$



Traveler's path choice

Minimizing travel time:

$$\min_{r \in \mathcal{R}^{od}} \sum_{a \in \mathcal{A}} \delta_{r,a}^{od} t_a(\mathbf{x}) \quad (= t_{r,op} + t_{r,p} + t_{r,pd}) \tag{2}$$

where,

r : path on the multi-layer network $r \in \mathcal{R}^{od}$

$t_a(\mathbf{x})$: travel time on link a, function of link flow $\mathbf{x}$

$\delta_{r,a}^{od}$: 1 if route r has link a as its element, 0 otherwise.

Modeling congestion

$x_a \setminus t_a$	Car	Parking	AMW	Waking
Car	✓	-	-	-
Parking	-	✓	-	-
AMW	-	-	✓	-
Walking	-	-	-	-

$$t_{a^c} = t_{a^c}(x_{a^c}, c_{a^c}), \quad dt_{a^c}/dx_{a^c} > 0 \tag{3}$$

$$t_{a^p} = t_{a^p}(x_{a^p}, c_{a^p}), \quad dt_{a^p}/dx_{a^p} > 0 \tag{4}$$

$$t_{a^m} = t_{a^m}(x_{a^m}, c_{a^m}), \quad dt_{a^m}/dx_{a^m} > 0 \tag{5}$$

$$t_{a^w} = t_{a^w}, \quad dt_{a^w}/dx_{a^w} = 0 \tag{6}$$

User equilibrium

Equilibrium condition:

$$\sum_{r \in \mathcal{R}^{od}} f_r^{od} = q_{od} \tag{7}$$

$$x_a = \sum_{od} \sum_{r} \delta_{r,a}^{od} f_r^{od} \tag{8}$$

$$f_r^{od} \geq 0 \tag{9}$$

$$t_r^{od} - u_{od} \geq 0 \tag{10}$$

$$(t_r^{od} - u_{od}) \cdot f_r^{od} = 0 \tag{11}$$

where,

q_{od} : given OD flow

f_r^{od} : flow of path r

x_a : flow on link a

u_{od} : minimum travel time between od pair od

Optimal AMWs installation problem

Optimization problem

$$\min_{\mathbf{y}} z(\mathbf{y}) = \underbrace{\beta \sum_{a \in \mathcal{A}} t_a(x_a) x_a}_{\text{total travel time}} + \underbrace{\omega \sum_{a^c \in \mathcal{A}^c} l_{a^c} x_{a^c}}_{\text{externalities of car traffic}} + \underbrace{\phi \sum_{a^m \in \mathcal{A}^m} l_{a^m} x_{a^m}}_{\text{AMW operation cost}} + \underbrace{\xi \sum_{a^m \in \mathcal{A}^m} l_{a^m} y_{a^m}}_{\text{AMW installation cost}} \quad (12)$$

where (the **decision variable** is),

y_{a^m} : 1 if AMW a^m is installed, 0 otherwise

subject to,

1. Equilibrium conditions Eqs.(7)-(11)
2. Network constraints (→ next slide)

Network constraints

1. **Space constraint** of streets:

$$\kappa_a = \sum_{s \in \{c,p,m,w\}} \kappa_a^s$$

2. **Physical constraints** of AMWs:
   - The minimum & maximum lengths:

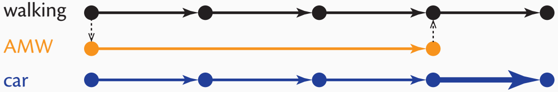
$$l_{\min} \leq l_{a^m} \leq l_{\max} \tag{13}$$

   - The minimum angle between streets:

$$\alpha_{a^m} \geq \alpha_{\min} \tag{14}$$

AMW representation

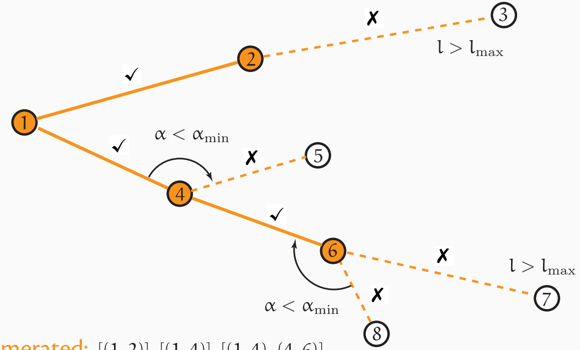
- An AMW can be placed across multiple streets:



- Representation:
  - (i^w, j^w): source and sink nodes on walking layer
  - $[(i, j), (j, k), \ldots]$: AMW elemental streets
  - l_{a^m} : length of AMW
  - α_{a^m} : minimum angle of two neighboring elemental streets

AMWs enumeration

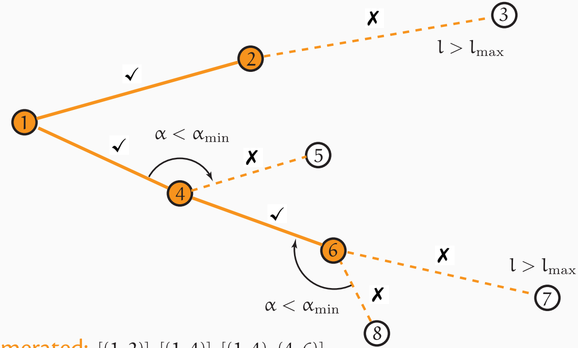
- Enumeration algorithm:



Enumerated: $[(1,2)], [(1,4)], [(1,4),(4,6)]$

AMWs enumeration

- Enumeration algorithm:



Enumerated: $[(1,2)], [(1,4)], [(1,4),(4,6)]$

- Iterate for all starting nodes and obtain AMW set A^m

Optimization algorithm

- Leader-follower (Stackelberg game) problem:
    1. Generate a **feasible solution y**
    2. Revise the network G
    3. Solve the **UE assignment x**
    4. Evaluate the objective function z
    5. Iterate Steps 1-4 until the algorithm terminates
- Searching algorithms:
    - Simulated annealing
    - Random addition/removal

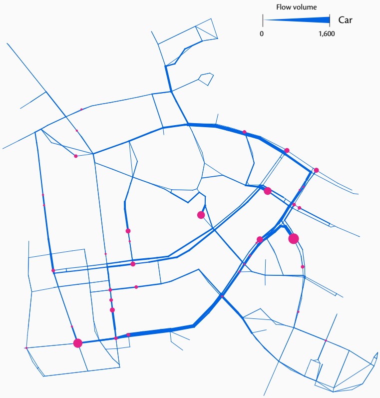
Case study

Case study

Berlin-Mitte network:

- **Network data** from 'Transportation Networks':
  - 796 nodes
  - 1,493 links
  - 36 zones
  - 1,260 OD pairs
  - 11,482 trips
- **Parking data** from 'Parkopedia'
  - 39 spots
  - Garages and open to public

Network flow pattern (original; without AMW):



Results

Network flow pattern (optimal; 157 AMWs):

Results

Objectives:

	original	optimal	random
Total travel time [h]	4,459	**4,164**	4,859
Total distance by car [km]	23,494	**12,350**	28,070
Total distance by AMW [km]	**0.0**	11,495	1,343
AMWs installation length [km]	**0.0**	35.0	17.1
$z(\mathbf{y})$ [EUR/day]	101,218	**86,863**	121,625

Closing remark

Conclusion

Contributions:

- AMWs installation to general networks
- A multi-layer network approach
- Congestion and capacity competition of mixed traffic

Next steps:

- Modeling congestion on AMWs in different ways
- Efficient solution algorithm
- Parking location & searching behavior

Questions?

Solution algorithms

Another algorithms tested:

- Local search (LS)
- Tabu search (TS)
- Variable neighborhood search (VNS-LS/VNS-TS)
- Cross entropy (CE) method

Results:

- Solving the UE once takes around 5 sec.
- LS/TS are very time-consuming $\rightarrow$ VNS is slow
- CE is slow to converge/improve

Parameter settings

Objective function:

- Value of time $\beta = 0.15$ [EUR/min]
- Externalities unit $\omega = 0.02$[EUR/g CO2] $\cdot$ 0.13[g CO2/km]
- AMW energy consumption $\phi = 0.00083$ [EUR/m $\cdot$ pax] [1]
- AMW installation cost $\xi = 0.22$ [EUR/m $\cdot$ day] [1]

Parameter settings

AMW:

- Minimum length $l_{\min} = 120$ [m]
- Maximum length $l_{\max} = 350$ [m]
- Minimum angle $\alpha_{\min} = 133$ [degree]
- Initial speed $v_0 = 0.75$ [m/s]
- Top speed $v_{\max} = 3.0$ [m/s]
- Walking speed $v_{\mathrm{walk}} = 1.34$ [m/s]
- Acceleration $a = 0.43$ [m/s2]

User equilibrium

Link performance function:

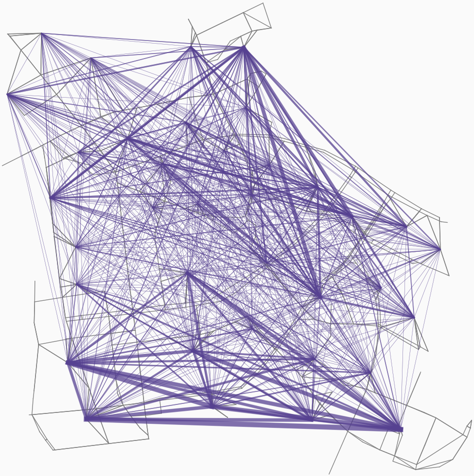
- $t_{a^c} = t_{a^c}(0) \cdot [1 + (x_{a^c}/c_{a^c})^4]$
- $t_{a^p} = 3 \cdot [1 + (x_{a^p}/c_{a^p})^4]$
- $t_{a^m} = t_{a^m}(0) \cdot [1 + 0.15(x_{a^m}/c_{a^m})^4]$

Solution methodology

- Frank-Walfe method
- Golden section method for linear search

OD demand

1,260 OD pair, 11,482 trips:



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