Analysis of Car-Free City Centers with a Dynamic Traffic Simulator

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Introduction

- Cities are creating **car-free areas** (or low-emission zones) in their city centers: area where no vehicle can enter, expect priority vehicles or buses
- Examples: Hamburg, Oslo, Madrid (Nieuwenhuijsen and Khreis, 2016, Nieuwenhuijsen et al., 2019)
- Main goal is **to reduce air and noise pollution and to increase green spaces** in the city center
- Impact on **road traffic** in the entire city

Research Question

Creating a car-free area implies a **reduction in the total capacity of the network**. Intuition suggests that **traffic congestion should increase**.

Braess Paradox: when the total capacity of the network decreases, traffic conditions can improve.

Can a Braess paradox occur when a car-free area is implemented?

Impact on Traffic Congestion

Different reasons can explain the occurrence of a Braess paradox:

- car drivers **shifting to other modes of transportation**;
- car drivers making a **detour** and thus decreasing congestion in the vicinity of the car-free area;
- car drivers **shifting to another departure time** to avoid the period with highest congestion.

Methodology

- Simulations with **METROPOLIS**, a dynamic traffic simulator
- **Circular city network** from de Palma, Kilani and Lindsey (2005), with 33 nodes and 128 edges
- Creation of a 1-km wide car-free area in the city center
- Intuitions for the results with an **analytical example**

Literature and Contributions

Impact of network capacity reduction on congestion:

- Braess (1968), Steinberg and Zangwill (1983): static models
- Arnott et al. (1993), Zhang et al. (2008), Lin and Lo (2009), Zhang and Zhang (2010): dynamic model with departure-time and route choice
- Thunig and Nagel (2016), Thunig et al. (2017): Braess paradox in a dynamic traffic simulator (exogenous departure time)
- This study: Braess paradox in a dynamic traffic simulator **(endogenous departure time, medium- and large-size network)**

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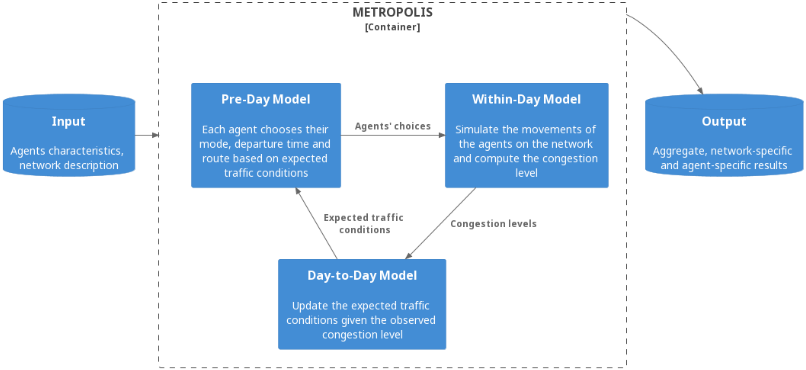
METROPOLIS Dynamic Traffic Simulator

- METROPOLIS is a **dynamic**, **mesoscopic** and **multi-modal** multi-agent simulator
- First version by de Palma, Marchal and Nesterov (1997)
- This work uses a new version, improving existing features (e.g., departure-time choice model, congestion model, route choice) and introducing new features (e.g., different vehicles, mode choice with arbitrary modes, public transit with in-vehicle congestion)

METROPOLIS Dynamic Traffic Simulator

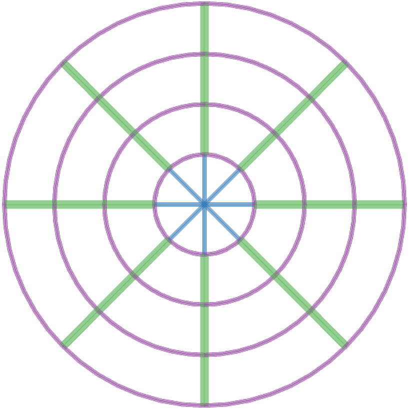


METROPOLIS Dynamic Traffic Simulator

- Continuous departure-time choice based on **Continuous Logit** theory (Ben-Akiva and Watanatada, 1981)
- The route chosen is the **fastest path on the time-dependent graph** (Batz et al., 2013)
- Congestion on an edge is represented by **speed-density functions** (running part of the edge) and **point bottlenecks** (queuing part of the edge)
- Traffic conditions are updated according to an **exponential learning process**

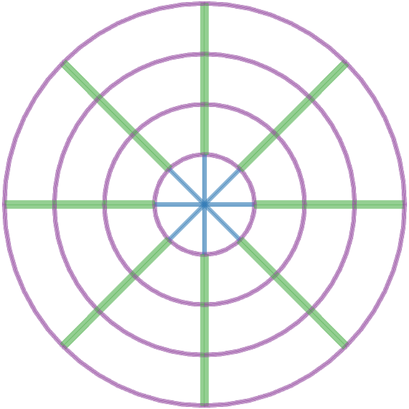
Circular City Network

	Purple	Green	Blue
Cap. (veh / h / lane)	Infinite	2000	500
Speed limit	50 km/h	70 km/h	50 km/h
Lanes	1	2	1



Population: Origin-Destination Matrix

- Same OD matrix as in de Palma, Kilani and Lindsey (2005).
- 33 origin or destination nodes.
- 264 000 car commuters (inc. 19 184 from / to the city center).



Population: Preferences

- **Generalized travel cost** ($\alpha - \beta - \gamma$ model: Vickrey, 1969, Arnott et al., 1990):

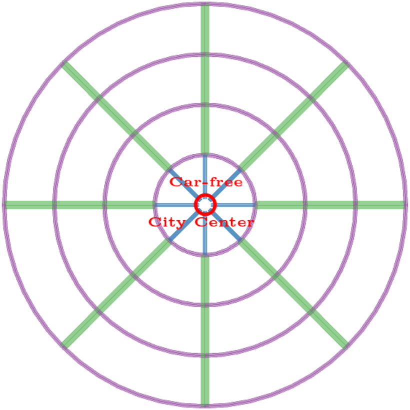
$$C(t_d) = \alpha \cdot tt(t_d) + \beta[t^* - t_d - tt(t_d)]^+ + \gamma[t_d + tt(t_d) - t^*]^+,$$

  with $\alpha = 10$, $\beta = 5$, $\gamma = 20$

- Desired arrival time t^* uniformly distributed between 7:30 and 10:30
- Mode choice is disabled

Network with a Car-Free City Center

- Car-free zone (in red) with a radius of 500 m
- Crossing the city center is no longer possible
- Assumption: Commuters coming from or going to the city center have to walk for 250m (3min at 5 km/h, i.e., an extra cost of 0.5 euros with a VOT of 10)



Aggregate Results without Congestion

	Baseline scenario	Car-free city center
Av. user surplus	14.12 euros	13.94 euros
Congestion level	0.00 %	0.00 %
Av. travel time (ex. walk)	15'38"	16'27"
Av. travel time (inc. walk)	15'38"	16'40"
Av. vehicle-km	15.25 km	15.93 km

Note: The user surplus is the expected travel utility resulting from the departure-time choice model.

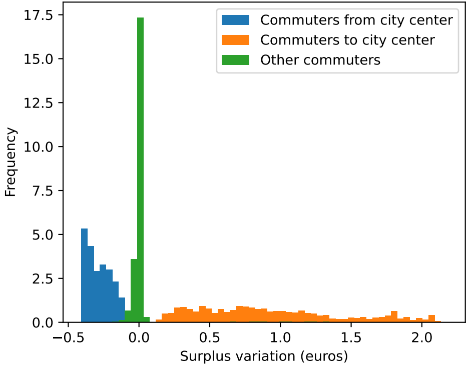
Aggregate Results with Congestion

	Baseline scenario	Car-free city center
Av. user surplus	13.72 euros	13.78 euros
Congestion level	9.66 %	5.25 %
Av. travel time (ex. walk)	18'04"	17'21"
Av. travel time (inc. walk)	18'04"	17'34"
Av. vehicle-km	15.79 km	15.80 km

Note: The user surplus is the expected travel utility resulting from the departure-time choice model.

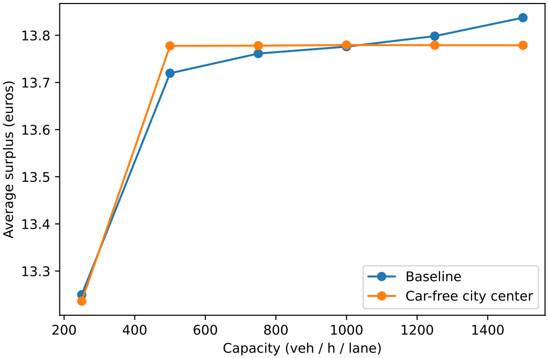
Distribution of Surplus Gains

- Commuters to the city center are better off (they face less congestion)
- Commuters from the city center are worse off (they have to walk to the outside of the car-free area)
- Other commuters have a similar surplus in the two scenarios



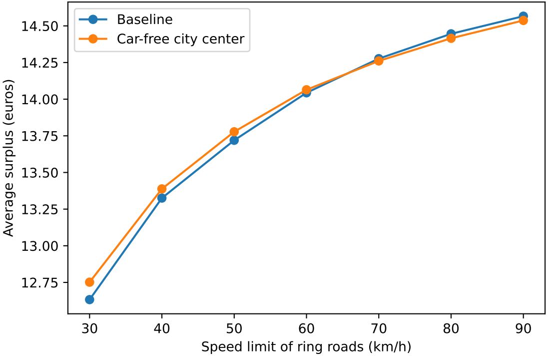
Comparative Statics: Impact of Road Capacity

Braess paradox only appears if capacity of the inner arterial roads is not too large and not too small



Comparative Statics: Impact of Ring Speed Limit

Braess paradox only appears if the speed limit for the alternative route is not too high



Analytical Example: A Toy Network

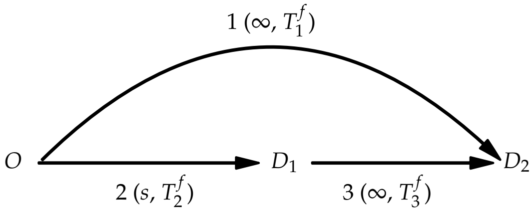
Three edges:

1. Edge 1, bottleneck of capacity $s_1 = \infty$, free-flow travel time T_1^f
2. Edge 2, bottleneck of capacity $s_2 = s$, free-flow travel time T_2^f
3. Edge 3, bottleneck of capacity $s_3 = \infty$, free-flow travel time T_3^f

Link travel-time is

$$tt_l(t) = T_l^f + \frac{Q_l(t + T_l^f)}{s_l},$$

where $Q_l(t + T_l^f)$ is the length of the queue of vehicles at the bottleneck of link l, at time $t + T_l^f$.

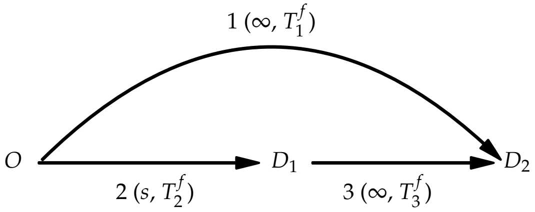


Analytical Example: Demand

- N_1 **type-1 commuters** traveling from O to D_1
- N_2 **type-2 commuters** traveling from O to D_2 (two routes: $O \to D_1 \to D_2$ or $O \to D_2$)
- **Travel cost**, for departure time t ($\alpha - \beta - \gamma$ model):

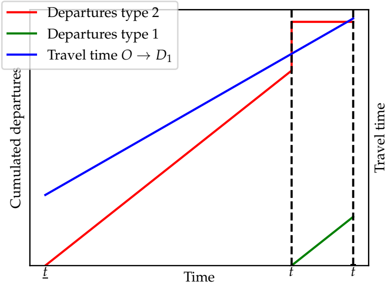
$$C(t) = \alpha \cdot tt(t) + \beta[t^* - t - tt(t)]^+ + \gamma[t + tt(t) - t^*]^+$$

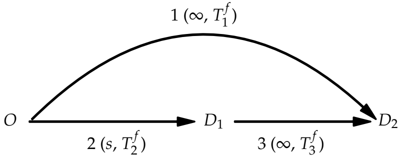
- α, β, t^* are homogeneous, γ is set to ∞



Analytical Example: Wardrop Equilibrium

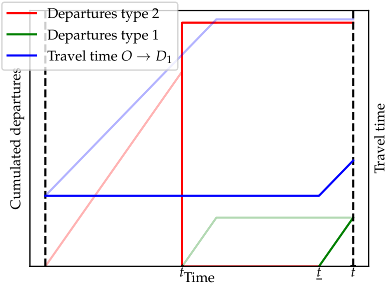
- From $\underline{t}$ to $\hat{t}$, type-2 commuters are leaving origin at a rate $s\frac{\alpha}{\alpha-\beta}$.
- From $\hat{t}$ to $\overline{t}$, type-1 commuters are leaving origin at a rate $s\frac{\alpha}{\alpha-\beta}$.

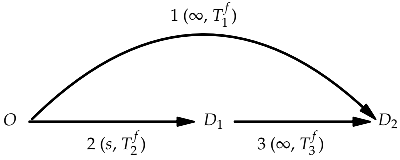




Analytical Example: Car-Free City Center

- D_1 becomes a car-restricted area
- Type-2 commuters have only one possible route, through link 1





Conclusion

- Car-free city centers can have a **positive effect on traffic conditions**
- The main winners are the commuters to the city center
- The impact of the car-free city center on congestion depends on the **capacity of the roads in the city center** and the **speed limit of the detour roads**

- Future works: time-dependent restriction, **full-scale application** to a large urban area

Thank you