On the distribution of urban road space for multimodal congested networks

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Highlights

- Understand multimodal interactions at the network level
- Model the aggregated dynamics of a multimodal system
- Integrate traffic dynamics in planning and design
- Optimize system performance with space distribution and pricing
Why Macro?

- Humans make choices of routes, destinations and driving behavior (unpredictability)
- Not a clear distinction between free-flow and congested traffic states (complexity)
- Need for real-time hierarchical traffic management schemes (efficiency)

Solution (?):
A network based aggregated approach

“With four parameters I can fit an elephant”. JOHN VON NEUMANN
Multimodal networks

- In urban networks, buses usually share the same network with the other vehicles.
- Movement Conflicts in multi-modal urban traffic systems.
- Bus stops affect the system like variable red signals in a single lane (instead of blocking all lanes).
- Increasing bus frequency decreases the flow of vehicles but can increase the flow of passengers.

\[
\min_{\pi_i(t)} Z = \sum_{t,i,m} PHT_{t,i,m}(\pi_i(t))
\]

**Performance Measures**
- Vehicle Hours Traveled
- Vehicle Kilometers Traveled
- Passenger Hours Traveled
- Passenger Kilometers Traveled

**Mobility (Accessibility)**
- Emissions (Environ. Impacts)
- Costs (Users, Providers, etc.)

**Road Space Used**

- Competing modes
- Parking
- Pax vs. veh throughput

MULTIMODAL CITIES
Motivation – A multi-modal MFD

Simulated data – Downtown San Francisco

Zheng et al. (2013) – Ongoing
Intro to Variational Theory

- VT estimates exactly the MFD for a ring with no turns.
- For networks, this estimation is an upper bound.
- Results from real cases show that this is almost tight for homogeneous distribution of congestion.

\[ q = \inf_u \{ku + R(u)\} \]

\[ R(u) = \lim_{t_0 \to \infty} \inf_{P} \{\Delta(P): u_{\hat{P}} = u\}/t_0 \]

Daganzo and Geroliminis (2008) – TR part B
Geroliminis and Boyaci (2012) – TR part B
Leclercq and Geroliminis (2013) - ISTTT
Variational Theory for multimodal networks
The effect of dwell times in network capacity

Methodology - General representation of a multimodal system

\[ \pi : \text{space share allocation} \]
\[ n(t) : \text{accumulation of vehicles (all modes) in the regions at time } t \]
\[ O(t) : \text{transfer flows (all modes) in the regions at time } t \]
\[ Q(t) : \text{generated demand per mode in the regions at time } t \]
\[ C(t) : \text{cost of travel in the regions at time } t \]
**Methodology - Traffic flow dynamics (1)**

- Mass conservation of vehicles (discretized):

\[
    n_{i}^{kc}(t + 1) = n_{i}^{kc}(t) + \frac{Q_{i}^{kc}(t + 1)}{ob_{i}^{c}} - \sum_{j=1}^{N} O_{i\rightarrow j}^{kc}(t) + \sum_{l=1}^{N} O_{l\rightarrow i}^{kc}(t), \quad \text{CAR}
\]

\[
    n_{i}^{kb}(t + 1) = n_{i}^{kb}(t) - \sum_{j=1}^{N} O_{i\rightarrow j}^{kb}(t) + \sum_{l=1}^{N} O_{l\rightarrow i}^{kb}(t), \quad \text{BUS}
\]

- \( n_{i}^{km}(t) \): accumulation of mode \( m \) in region \( i \) with next destination region \( k \) at time \( t \)
- \( O_{i\rightarrow j}^{km}(t) \): transfer flow of mode \( m \) from region \( i \) to \( j \) with final destination \( k \) at time \( t \)
- \( Q_{i}^{km}(t) \): demand generated \( k \) at time \( t \) in region \( i \) with next destination region \( k \), choosing mode \( m \)
- \( ob_{i}^{c} \): average number of passengers per car in region \( i \)
Methodology - Traffic flow dynamics (2)

- Conservation of passengers:

\[ OB_{i}^{kb}(t + 1) = OB_{i}^{kb}(t) + Q_{i}^{kb}(t + 1) - \sum_{j \neq i}^{N} O_{i \rightarrow j}^{kb}(t) \cdot ob_{i}^{kb}(t) + \sum_{l=1}^{N} O_{i \rightarrow l}^{kb}(t) \cdot ob_{l}^{kb}(t) - b_{i}^{k} \cdot OB_{i}^{kb}(t) \cdot (1 - (1 - \theta_{i})^{z}) \]

\( OB_{i}^{kb}(t) \): the number of bus on-board passengers currently in region \( i \) with final destination \( k \)

\( ob_{i}^{kb}(t) \): the average number of on-board passengers per bus from region \( i \) to \( k \)

\( b_{i}^{k} \): binary variable indicating if reaching destination, \( b_{i}^{k} = 1 \) for \( i = k \) and 0 otherwise

\( \theta_{i} \): probability of reaching destination

\( z \): number of stops that a bus travels during interval \( t \)

\( \theta_{i} \) is a Bernoulli trial repeated \( z \) times, \( \theta_{i} = \left( \frac{\bar{L}'_{ib}}{S_{i}} \right)^{-1} \), where \( \bar{L}'_{ib} \) is the trip length \( S_{i} \) and is the bus station spacing

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Methodology – Multimodal travel time estimation

- Speed estimation for single-mode only region:
  \[ V_i^m(t) \overset{\text{def}}{=} \frac{P_i^m(t)}{n_i^m(t)} = \frac{O_i^m(t) \cdot \bar{L}_{im}}{n_i^m(t)} \]

- Speed estimation for mixed mode region:
  \[ V_i^b(t) = V_i^c(t) \cdot \alpha_i^b(t), \quad \alpha_i^b(t) = \frac{TT_i^b(t)}{TT_i^b(t) + TT_d^b(t)} \]

- Travel time estimation:
  \[ TT_i^m(t) = \frac{\bar{L}_{im}}{V_i^m(t)} \]

- Assumptions:
  Buses travel with the same speed of cars, if not dwelling for passengers
Methodology – Mode choice

- Utility of traveling by each mode:

\[ U_{i}^{kc}(t) = - \sum_{j \in \{s_{i}^{k}\}} (TT_{c}^{i}(t) + C_{j}^{c}(t)), \quad U_{i}^{kb}(t) = - \sum_{j \in \{s_{i}^{k}\}} (TT_{j}^{b}(t) + D_{j}^{b}(t)) \]

- Mode choice calculation:

\[ p_{i}^{kb}(t + 1) = p_{i}^{kb}(t) + \beta_{1} \cdot \Delta U_{i}^{k}(t) + \beta_{2} \cdot (\Delta U_{i}^{k}(t) - \Delta U_{i}^{k}(t - 1)) \]

\[ U_{i}^{km}(t) : \text{Utility of traveling by mode } m \text{ from region } i \text{ to } k \text{ at time } t \]
\[ C_{j}^{c}(t) : \text{cost other than travel time for using cars in region } j \text{ at time } t \]
\[ D_{j}^{b}(t) : \text{discomfort for using buses in region } j \text{ at time } t \]
\[ p_{i}^{kb}(t) : \text{percentage of the demand generated at time } t \text{ in region } i \text{ choosing mode bus} \]
Methodology – Optimization framework

- System performance measure:

\[ PHT(\pi) = \sum_{t} \sum_{i} \sum_{k} (n_{i}^{kc}(t) \cdot ob_{j}^{kc} + OB_{i}^{kb}(t)) \cdot T \]

- Objective function:

\[ \min_{\pi_{i}(t)} Z = \sum_{t,i,m} PHT_{t,i,m}(\pi_{i}(t)) \]

\( \pi_{i}(t) \): the space distribution plan for region \( i \) at time \( t \)

- Optimization algorithm: Lagrangian SQP with multiple initial search
Case study set-up

- Mixed traffic in periphery
- Dedicated bus lanes in center

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Results - Optimal *static* space distribution

Space efficiency for all modes (trips/ln-km):

Space efficiency for bus lanes (trips/ln-km):
Results - Optimal *dynamic* space distribution
Results - Optimal *dynamic* space distribution & *pricing*

- More reliable MFD states
- TOLL = DELAY SAVINGS
- Robust in demand uncertainty
- Robust in Demand increase
Results – Demand Increase

- Fixed pricing
- Optimal pricing
- No pricing

PHT (person-hrs)

Bus occupancy (pax/bus)

Demand increase

Toll price (in CHF)

Accumulation

Outflow

15% increase

25% increase

No pricing

Pricing of the base case

Pricing for optimal PHT
Ongoing work

- Deeper analysis of multiple regions
- Incorporating cruising-for-parking + restriction/pricing
- Combining space distribution with signal control, bus priority
- Intergrating additional modes
- Validation with field-data
- Heterogeneity among users and different regions