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Intelligent Urban Transportation – Making Last Mile Deliveries more Efficient, Reliable and Sustainable

UMSL, 2015-11-06

Jan Fabian Ehmke

Advanced Business Analytics Group
School of Business & Economics
Freie Universität Berlin

Based on joint work with
Ann Campbell – André Steinert – Barrett Thomas – Tim Urban

Intelligent Urban Transportation

Aim: making urban transportation more efficient, reliable and sustainable

- Individual mobility
  - Sharing of mobility resources
  - Automation leads to increased dynamics of systems
- Transportation of goods
  - Narrow service time windows (→ efficiency & reliability)
  - Minimize emissions (→ efficiency & sustainability)
- Aggregation of operational data
  - Ubiquity of sensors
  - Transactions
- Intelligent data analysis and data mining
- Dynamic and stochastic optimization

Challenges for Urban Deliveries

- Online retailing is the fastest growing retail sector
- **Efficient and reliable** deliveries are critical for lasting success
- This is particularly challenging for **attended deliveries**
  - Examples: grocery, large appliances, repairmen
- Customers expect **on-time deliveries** and narrow service time windows
- Logistics service providers need to find **the optimal trade-off** between efficiency, reliability and sustainability
- Metropolitan areas suffer from **congestion** and **pollution**

E-Commerce

EBay and Amazon Eye Same-Day Delivery

By Meghan Walsh on August 10, 2012

Amazon's 'Monumental Bet'

Jay Yarow | Sep. 12, 2012, 9:31 AM | 10,157 | 12

Bloomberg Businessweek BUSINESS INSIDER

Agenda

- Collect, Analyze and Transform Sensor Data
- Set up a Planning Framework for Urban Routing

Setup

- Decide Which Customers to Accept
- Find a Balance between Efficiency and Reliability

Efficiency

- Ensure Service Levels in Routing
- Investigate the Theoretical Potential of Reliability

Reliability

- Consider Sustainability in Routing
- Assess the Importance of Stochastic Travel Times for Minimizing Emissions

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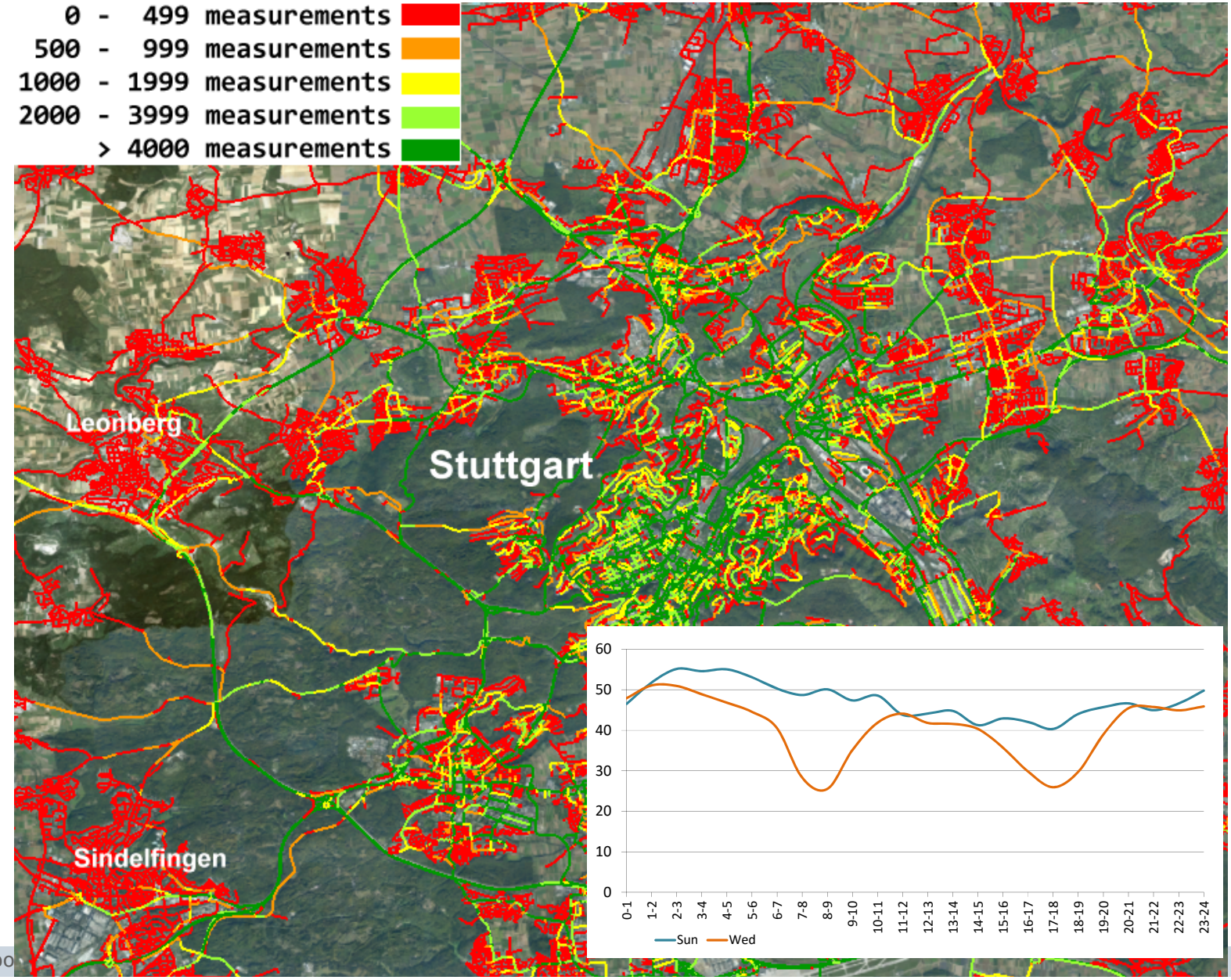
Ubiquitious Sensor Data

~230 million Floating Car Data from taxis

Network of
~ 100000 links
~ 128000 nodes

Aerial view with kind permission of GeoContent, Magdeburg



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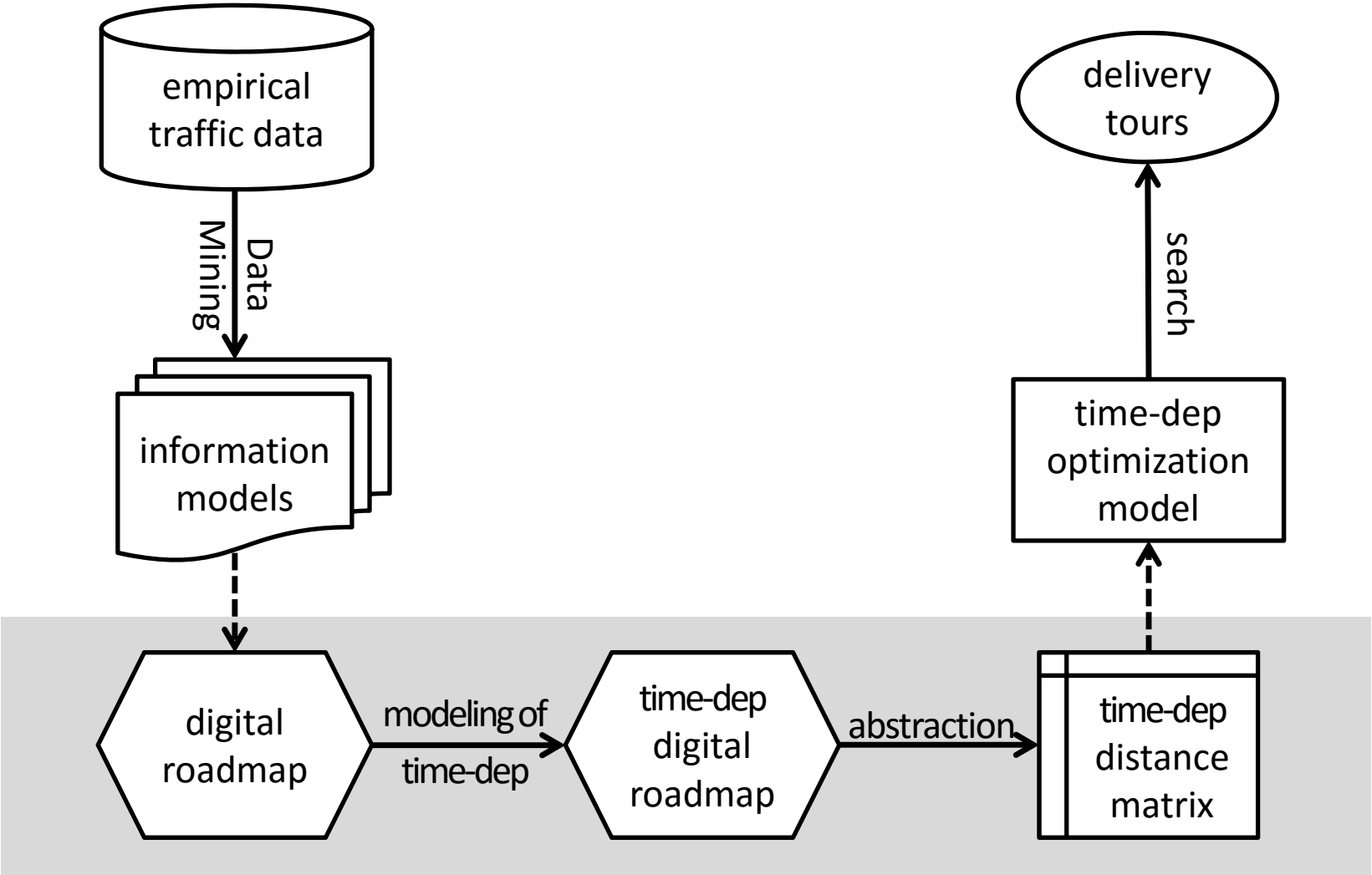
A Planning Framework for Urban Transportation



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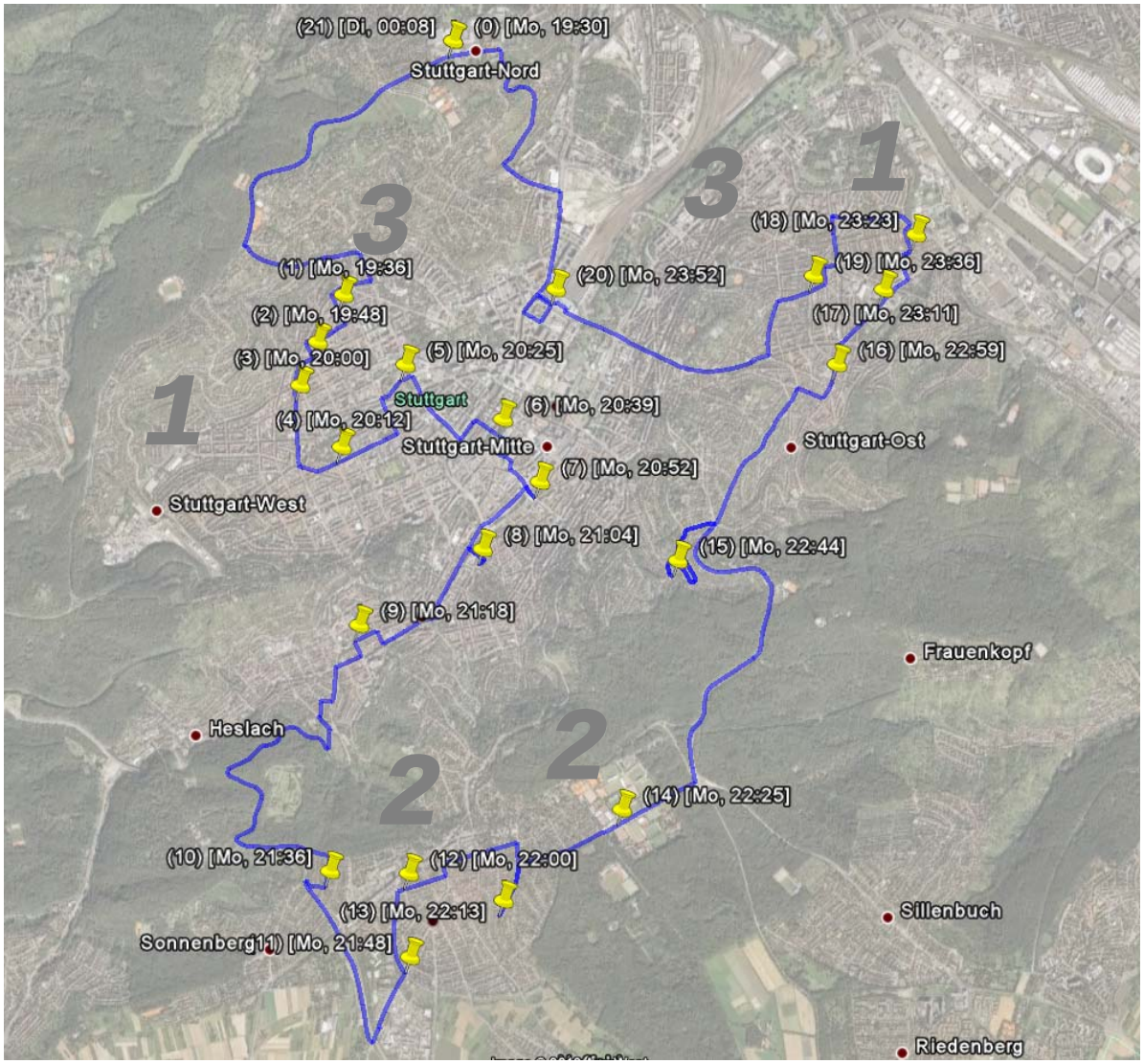
Time-Dependent Routing



- Optimization of a single route
- The optimal order of customers depends on the **departure time**

Examples for departure at

- 13:30
  → Return at 18:16
- 19:30
  → Return at 00:08

- Time-dependent routing follows **anticipated congestion** of the urban traffic network

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Maximize the Number of Customers

- We want to maximize the number of customers we can serve considering **tight time windows**
- How do we decide which customers to accept?
- How do we **balance** profit maximization with the need to provide reliable service?
- Examine several **acceptance mechanisms**
  - Differ in level of information, ease of implementation
- Evaluate them using **simulation framework**
  - Simulated demands
  - Simulated travel times to reflect congestion in metropolitan areas

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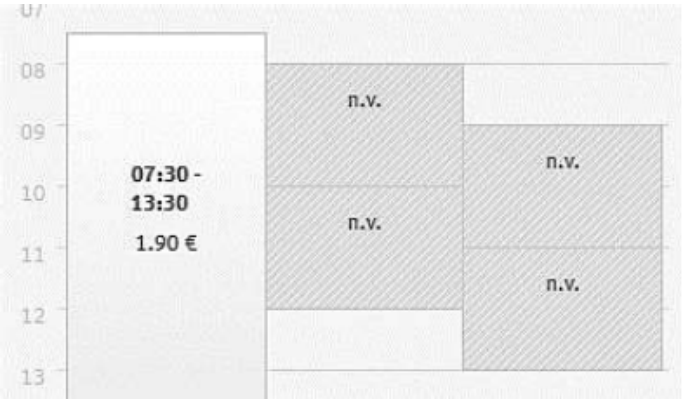
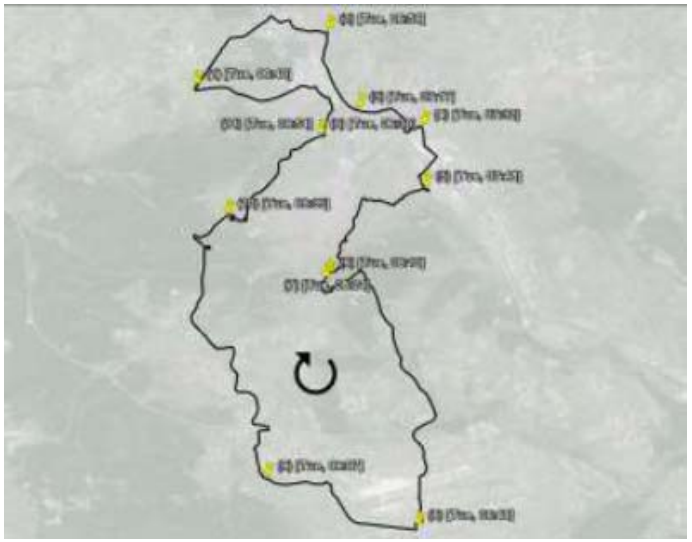
Customer Acceptance – Related Work

- **Selection** of a service time window
  - Maximize profits by accepting as many customer requests as possible while ensuring service quality
  - Decide on when to open and close time windows
  - Assumed deterministic travel time
  - Not look at impact of congestion/time dependency
  - Campbell & Savelsbergh 2005/2006, Asdemir et al. 2009



- **Vehicle routing** and scheduling
  - Minimizing costs of delivery
  - Consider time-dependent travel times
    → time-dependent VRPTW
  - Ichoua et al. 2003, Eglese et al. 2006, Fleischmann et al. 2004, Maden et al. 2010



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Home Delivery Problem – Problem Setting

- Retailer offers a **predefined set of time** slots on a day
- Delivery requests arrive before start of service

- Customer selects time slot
  - Each customer has first and second choice
  - Provide first choice if available
  - Provide second choice if first choice not available
  - Customer leaves if neither is available

- Need to quickly decide if a request can be handled in a particular time slot

- Objective: **maximize the number of accepted requests** (assumption: vehicle capacity not binding)

Time Slot
[12:00,12:59]
[13:00,13:59]
[14:00,14:59]
[15:00,15:59]
[16:00,16:59]
[17:00,17:59]
[18:00,18:59]

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Home Delivery Problem – Solution Approach

- Need to quickly decide if a request can be handled in a particular time slot
- This can be done in a rough/approximate way
  - Rules of thumb
  - Fast/easy
- Refer to as **static approaches**
- This can be done in a more dynamic way
  - Use more detailed information, build routes
  - Can accept more deliveries
  - May accept too many deliveries!
  - Congestion, stochastic travel times
- Refer to as **dynamic approaches**

Time Slot
[12:00,12:59]
[13:00,13:59]
[14:00,14:59]
[15:00,15:59]
[16:00,16:59]
[17:00,17:59]
[18:00,18:59]

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Dynamic Approaches (1/2)

- **Dynamic (DYN)**
  - Incorporate time-dependent travel times and precise routing
  - Consider a time-dependent routing solution for feasibility check (I1/Solomon 1987)
  - If the current request (and the already accepted requests) can be accommodated feasibly, the request is accepted
  - This can still fail due to stochastic travel times!

- **Dynamic Simple Buffer (DYN-SBF)**
  - Include a simple buffer time bt in the feasibility check of each request
  - Accept a request i only if $arr_i + bt < late_i$
  - E.g. get there 10 minutes before window closes
  - All customers have the same buffer

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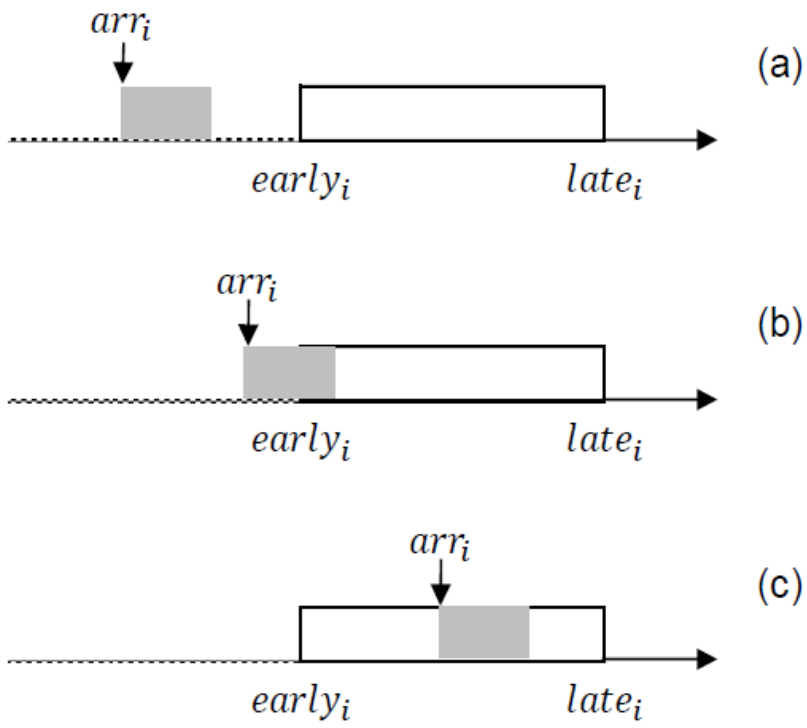
Dynamic Approaches (2/2)

- **Dynamic Buffer (DYN-BUF)**
  - Accept a request i only if $arr_i + bt_i < late_i$
  - Computing this buffer correctly is non-trivial!



- Idea: recursive calculation of variance that depends on
  - Proportion β_i of arrival time distribution after $early_i$
  - Variation of travel times $\sigma^2_{i-1,i}$
  - y_i = cumulated standard deviation of arrival time
  - $y_i = \sqrt{\beta_{i-1}\gamma^2_{i-1} + \sigma^2_{i-1,i}}, \gamma_0, \beta_0 = 0$
  - $bt_i = \alpha\, \beta_i \gamma_i$
    (with user specific service level α)

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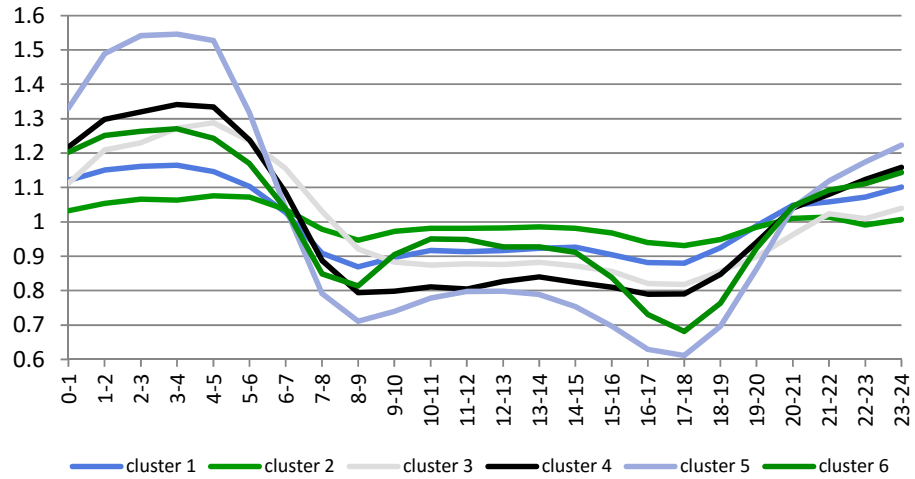
Experimental Design

- Real-world inspired urban road network
- Time-dependent travel times generated from speed multipliers
  - To reflect daily congestion patterns
- Two zones of customer locations
  - Inner city and suburbs

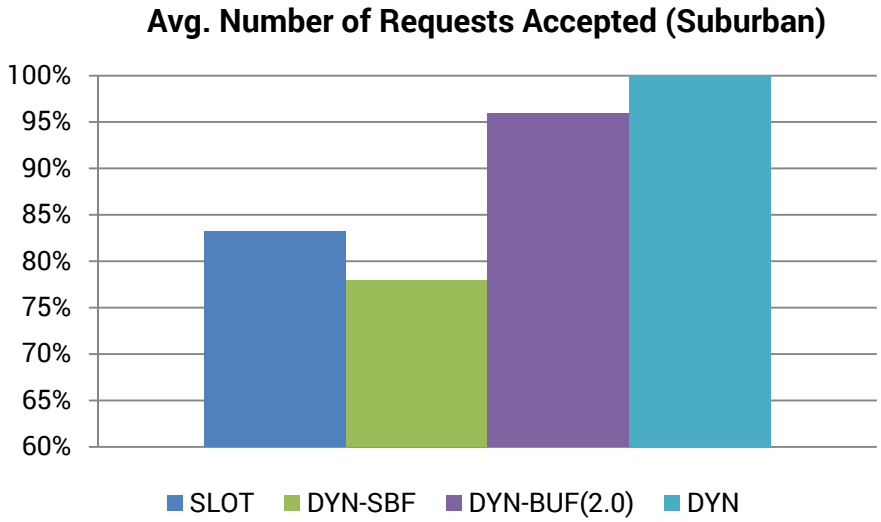


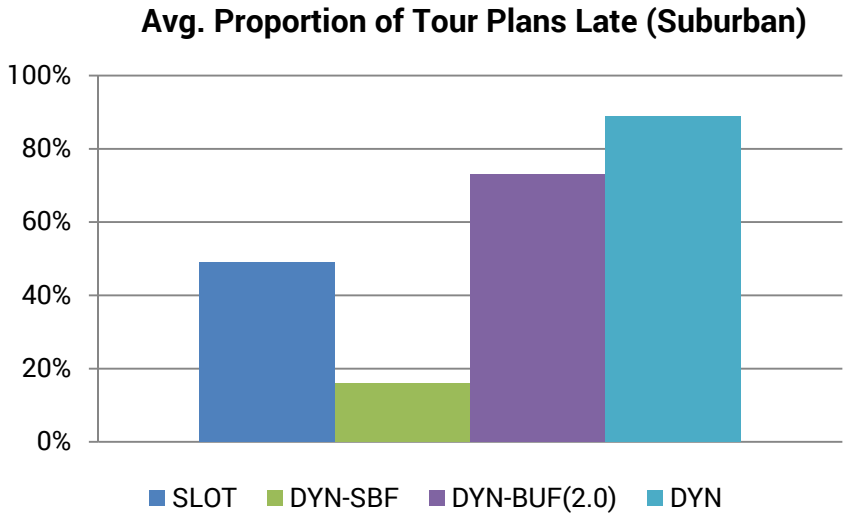
- Random generation of customer requests with random selection of time windows
  - 100 instances from each zone
  - Simulated 1000 times
- Basic test
  - Time windows width of 60 minutes
  - Service time of 20 minutes
  - Three vehicles


Impact of DYN-BUF
[7] [6]
TW 15:00-16:00
DYN: Arrival 15:56
BUF: Arrival 15:32
[6] [6]
TW 15:00-16:00
DYN: Arrival 15:59
BUF: Arrival 15:51
[10] [9]
TW 17:00-18:00
DYN: Arrival 17:46
BUF: Arrival 17:35
TW 18:00-19:00
DYN: Arrival 18:58
BUF: Arrival 18:14
[10] [11]
TW 19:00-20:00
DYN: Arrival 19:42
BUF: Arrival 19:28
DYN: 34 customers
Proportion served late: 94%
BUF: 34 customers
Proportion served late: 7%
[12] [12]

Suburban Delivery

- DYN-SBF accepts the least requests with 10 minute buffer
- DYN accepts the most but is late in 89% of realizations
- DYN-BUF: slightly smaller request acceptance, but occurrence of lateness is reduced a lot
- SLOT accepts far fewer but is also rarely late – tends to be conservative





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Ensure Service Levels in Routing

- We aim to minimize costs of delivery and ensure **a given service level** for all customers (“chance constraint”)
- Related work mainly focuses on recourse, i.e., arrivals before and after service time windows are **penalized** (“soft time windows”; Taniguchi et al. (2001), Ando and Taniguchi (2006), Tas et al. (2013a), Tas et al. (2013b))
- Carefully consider how to **compute arrival time distributions** for each customer
- Enhance **feasibility check** such that it can be “plugged” into any algorithm for the VRPTW

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Service Levels – Problem Setting

- Based on standard VRPTW formulation: One depot with a set of identical vehicles; each customer has a **service time window** $[early_i, late_i]$

- Travel time from customer i to customer j is **stochastic** (but not time-dependent)
  - We first assume normally distributed travel times
  - Travel times are statistically independent
  - We are particularly interested in distributions of the arrival time AT_i and start of service time ST_i

- Objectives
  - compute tour plan with (1) minimum number of vehicles and (2) minimum total tour duration;
  - ensure that the probability of arriving at each customer i by $late_i$ is **greater or equal to a given service level** α, i.e., $P(AT_i \leq late_i \forall i) \geq \alpha$.

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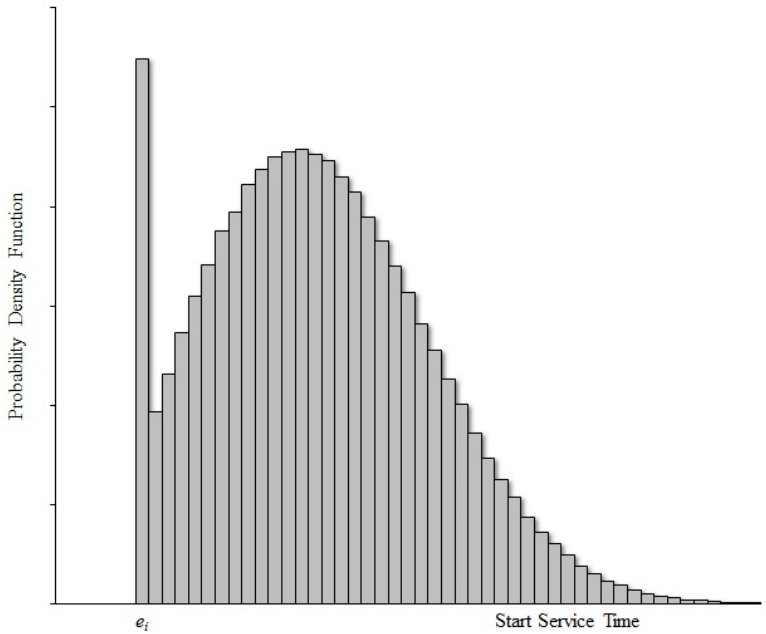
Propagation of Arrival Times

- To verify a certain probability of arriving at each customer i by $late_i$, we must know the distribution of AT_i

- The expected arrival time at a customer i is based on **previous travel times and service time windows:**
  - In case of **no waiting** on the route to i: means and variances can be summed according to the convolution of the normal distribution
  - In case of **waiting** with high probability: start of service will be at e_{i-1}; variance at customer i will be due to the travel time between $i-1$ and i
  - In case of relatively low probability of waiting: carefully consider how this affects the distribution of ST_{i-1}
    → **combine start of service time and travel time distributions**



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Extending Feasibility Checks for the VRPTW

- We enforce

$$\mathrm{P}(AT_i \leq late_i) \geq \alpha$$

  based on the particular arrival time distribution generated by **extreme value theory**

- More formally, for each customer i, we guarantee

$$\mu_{AT_i} + z_\alpha \sigma_{AT_i} \leq late_i$$

- We embed the feasibility check and the computation of arrival and start-service times in a **tabu search algorithm** (LANTIME, Maden et al. (2010))

- We adapted the way LANTIME handles infeasible solutions

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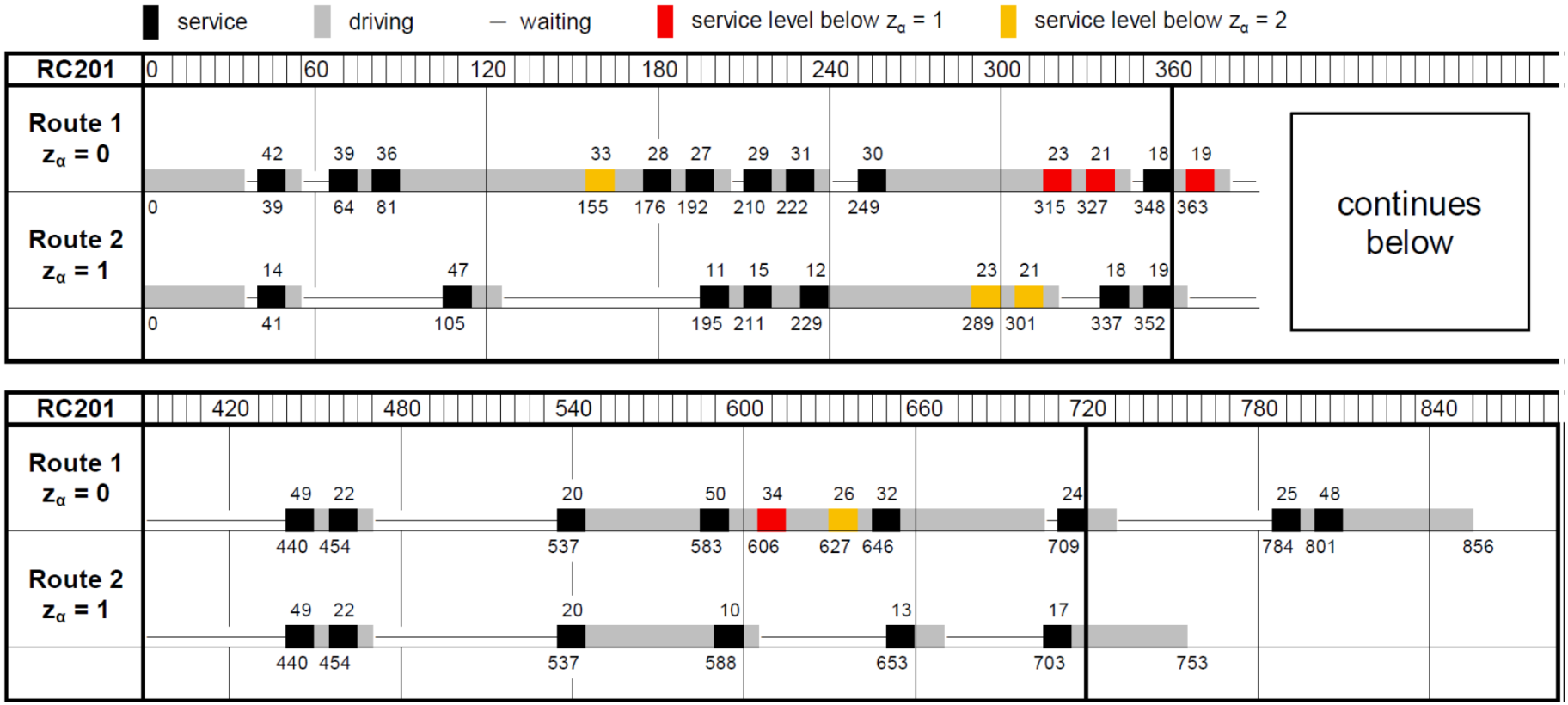
Computational Experiments (1/2)

- Computational experiments based on **Solomon benchmark data sets**
  Mean travel time is based on Euclidean distance with CoV = 20% or CoV = 40%
- We consider three **different service levels** ($\alpha = 50\%, 84.13\%, 97.73\%$)



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Computational Experiments (2/2)

- R1: randomly distributed customers, routes with few customers, tight service time windows

num	CoV	z_α	vehicles	% incr	time	% incr
			Route construction			
50	0.2	0	9.2	–	874.1	–
50	0.2	1	10.0	9%	899.0	3%
50	0.2	2	10.6	15%	967.5	11%
50	0.4	0	9.6	–	873.4	–
50	0.4	1	11.0	15%	973.7	11%
50	0.4	2	12.8	33%	997.5	14%
100	0.2	0	15.6	–	1386.5	–
100	0.2	1	17.8	14%	1410.8	2%
100	0.2	2	18.4	18%	1515.9	9%
100	0.4	0	16.0	–	1495.7	–
100	0.4	1	18.6	16%	1504.0	1%
100	0.4	2	20.0	25%	1620.3	8%

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Consider Sustainability – Minimize Emissions

- Increasing transportation activities induce **higher emission rates** (→ greenhouse gas emissions)
- Focus of routing is on **distances** & **travel times**
- How different are distance and travel-time based routes compared to emissions-minimized routes?

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- Include **emissions objectives**, esp. load
- Consider **detailed information** on time-dependent speeds from historical speed database
- Find a **computationally tractable way** to adapt vehicle routing heuristics

Saving Fuel: UPS Saves Fuel and Reduces Emissions the "Right" Way by Avoiding Left Turns

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Minimize Emissions – Problem Setting

- Based on a standard VRP setting
  - Given fleet of vehicles
  - Customers with pickups of a **particular weight**
- Emissions are modeled using the **Comprehensive Emissions Model (CEM)** (Barth et al. 2005)
- Load will **vary** on the paths between the customers
  - What is the **emissions optimal path** for a given load and departure time?
  - Paths **cannot** be precomputed in general!

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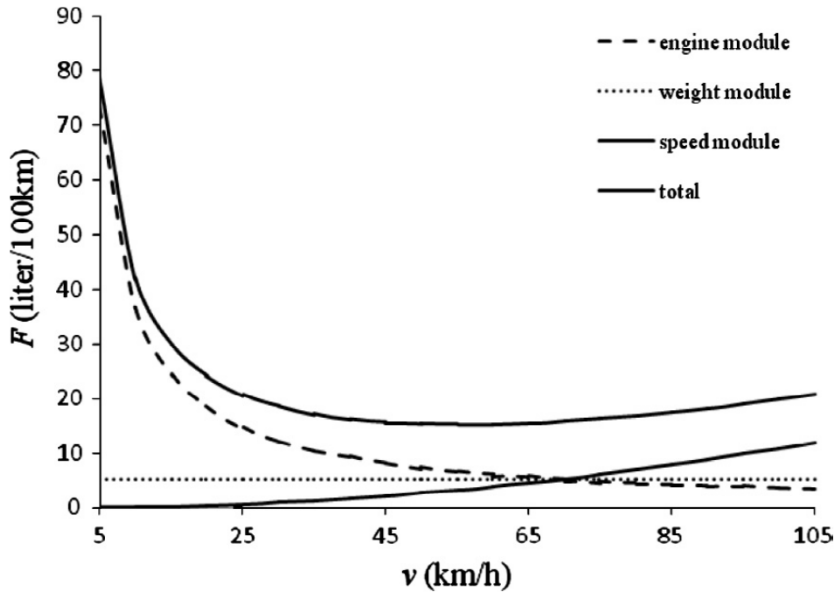
Modeling Emissions

- Emission is a function of speed, distance, and weight of a vehicle

- **CEM** modified for time-dependent fuel consumption on arc *a* at time *t* and load *l*

$$F_a(t,l) = E\left[\lambda\left(kN_eV\frac{d_a}{v_{a,t}} + \gamma\beta d_a v_{a,t}^2 + \gamma\alpha(\mu + l)d_a\right)\right]$$

  - With d_a as distance, $V_{a,t}$ as speed, and *l* as load
  - λ, k, γ, β, and α as engine specific parameters



- Relationship between speed and emissions is **non-linear**

- Optimization based on **mean speeds** underestimates emissions (Jensen's Inequality $f(E[V_e]) \leq E[f(V_e)]$)

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Related Literature

- Is based on different emissions models (popular: CEM and MEET)
- Often assumes that vehicles can drive with emissions-minimizing speed (Bektas and Laporte (2011) and Demir et al. (2012))

- Considers congestion by means of time-varying travel times and speeds (Figliozzi (2010), Jabali et al. (2012), Franceschetti et al. (2013))
- Also related: VRPs considering congestion charge (Wen et al. (2014), Qian and Eglese (2014))

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Intelligent Precomputation

- Vehicle routing heuristics usually require the **precomputation** of expected emissions costs
  - between every pair of customers
  - at each departure time
  - for every possible load

- Precomputation is conducted by **shortest path algorithms**
  - How to handle varying load sizes?

- **Proposition:** *If a path between a pair of nodes is optimal in terms of emissions for an empty truck as well as a full truck, the path is optimal in terms of emissions for all load sizes in between.*

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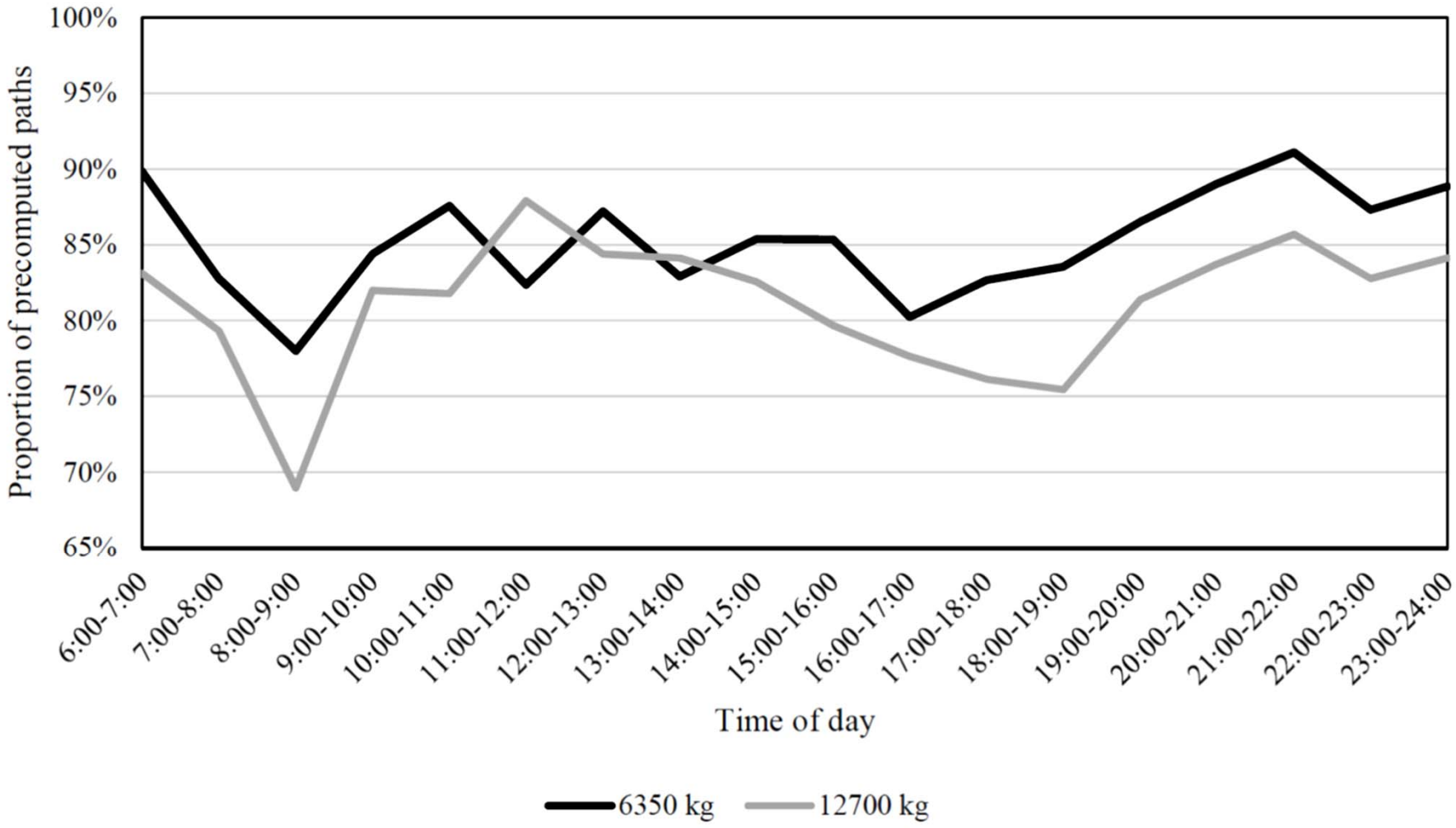
Value of Intelligent Precomputation



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Routing Algorithm

- We employ a well-known **tabu search** solution approach (LANTIME; Maden et al. 2010)
- We adapt standard tabu search neighborhoods
- An initial solution is constructed with **I1** (Solomon 1987)

- Primary objective: minimize the **number of vehicles**
- Secondary objective: minimize the **total expected emissions costs**

- **Lookup** precomputed, load-independent emissions costs and add load-dependent costs when load is known
- If lookup fails, compute and store emissions cost for a particular load **online**

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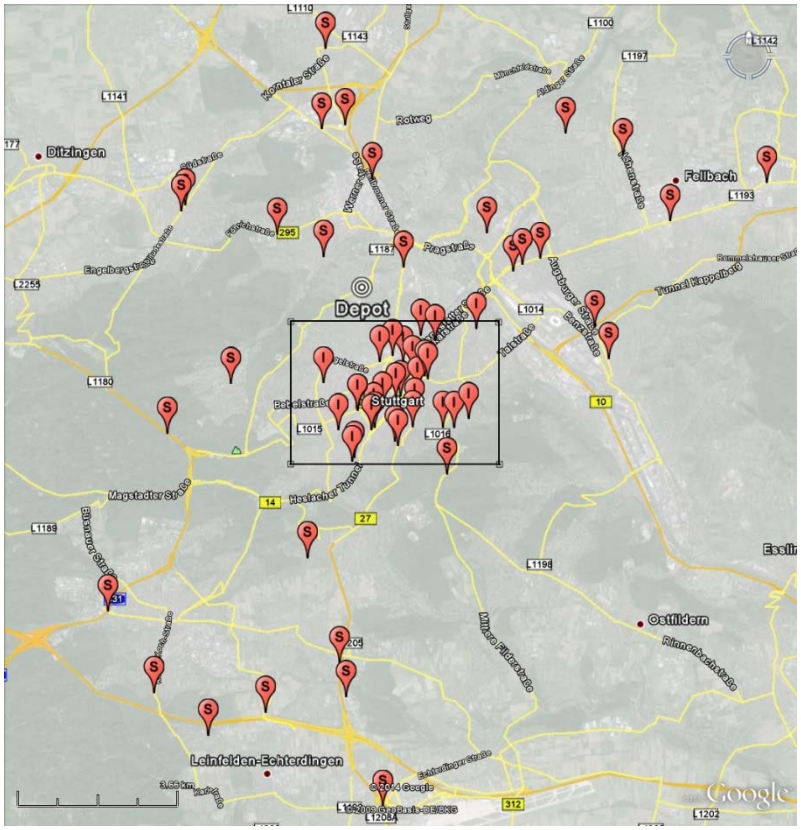
Computational Setup

- Four **departure times** on Tuesdays (06:30, 12:30, 15:30, 19:30)
- Five **test sets** with 10/30 customers each (inner city, suburban, mixed)

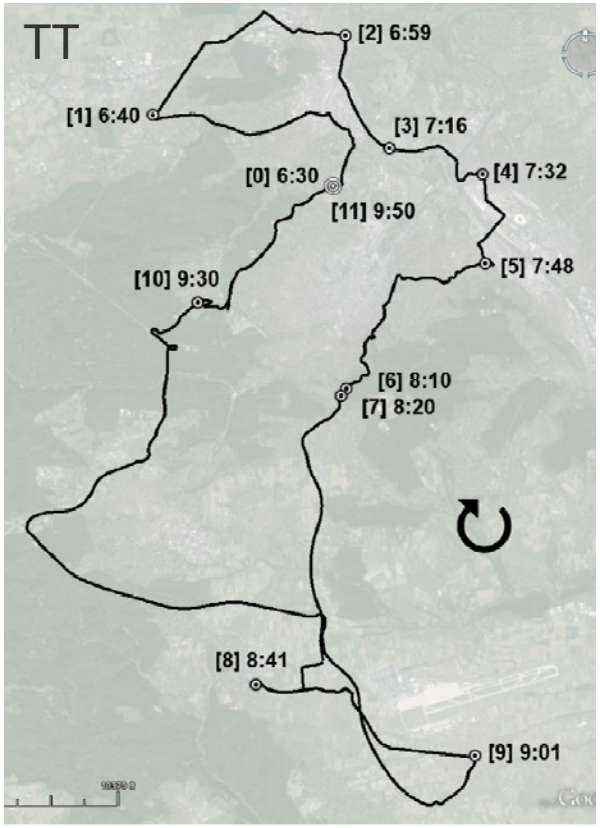
- Two different **types of vehicles** (standard, heavy)

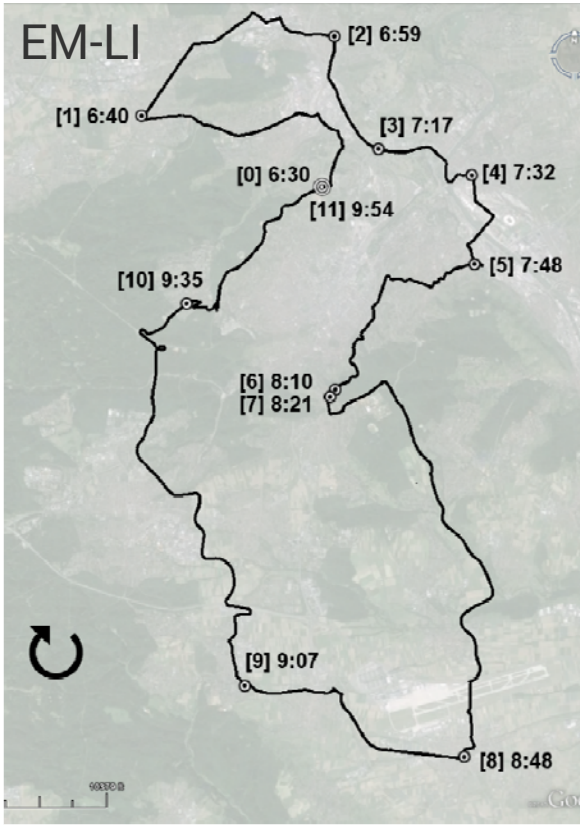
- **Heterogeneous load**: select three customers whose load totals 90% of capacity (random, farthest, closest)
- **Homogeneous load**: divide the space evenly between the customers

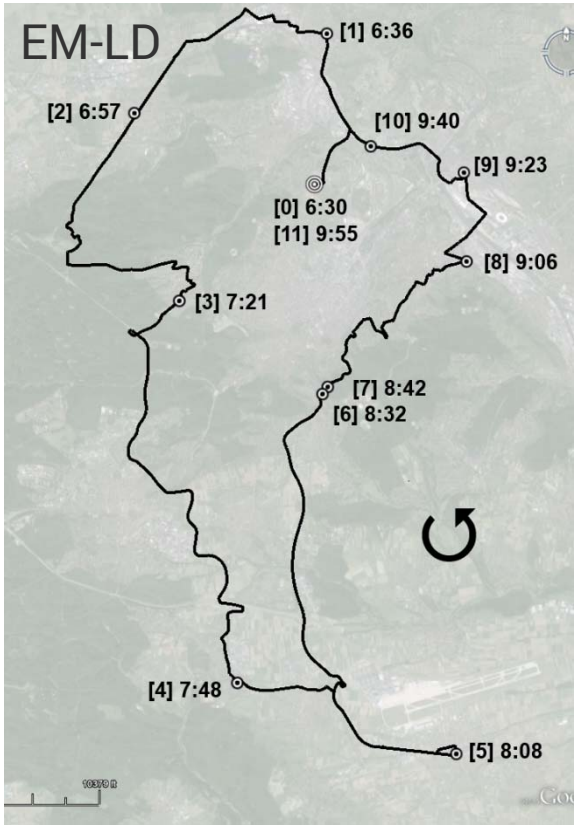


- **Multiple vehicles**: compare results for 30 customers on different fleets (standard, heavy, mixed)

TSP: Examples for Homogeneous Loads







- TT: clockwise, total length: 73.71 km, total emissions: 17.63 kg CO_2
- EM-LI: avoids highways, total length: 66.75 km, total emissions: 15.55 kg CO_2
- EM-LI: counterclockwise, total length: 66.10 km, total emissions: 15.40 kg CO_2

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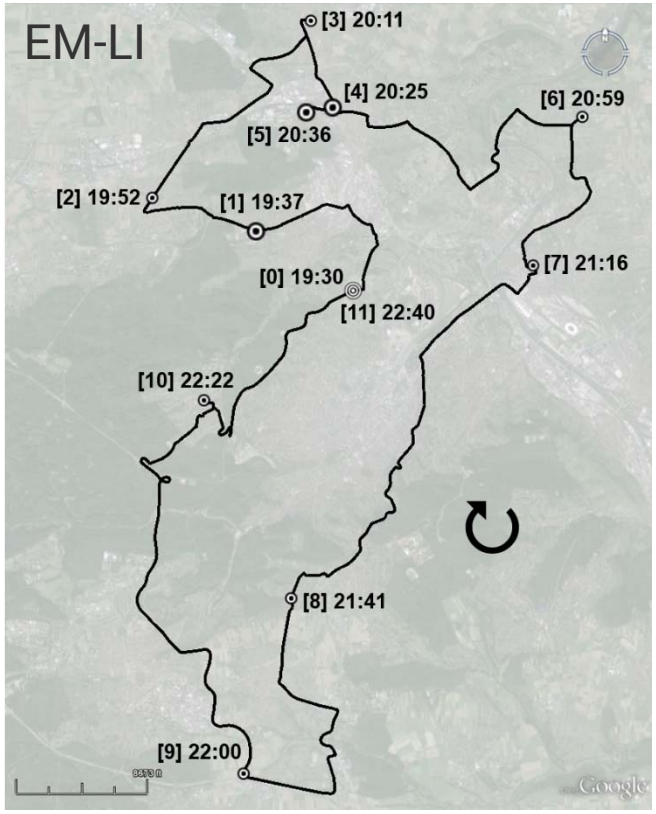
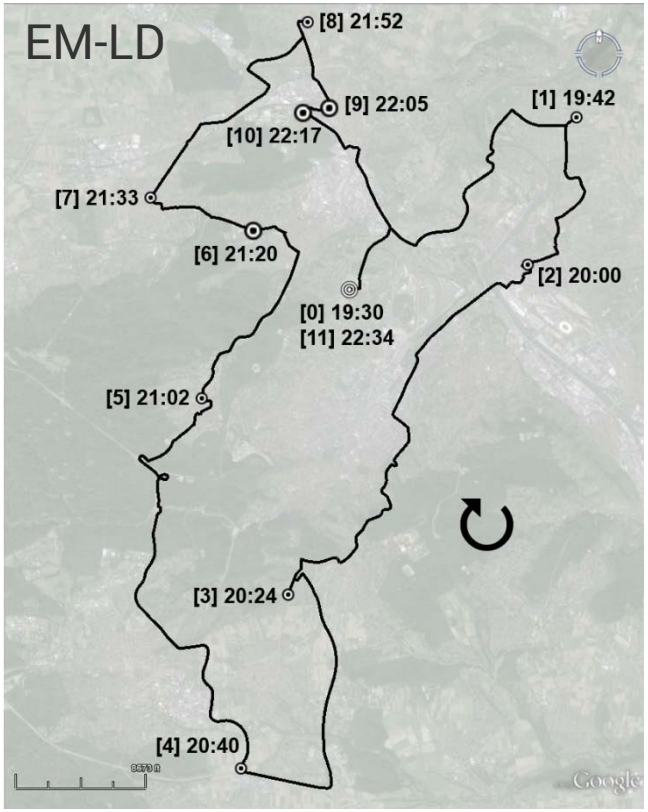
TSP: Examples for Heterogeneous Loads





Three Closest Customers Heavy

- EM-LI route serves heavy customers early in the tour
- EM-LD route: heavy customers are shifted to the end
- 4 kg Savings in CO_2

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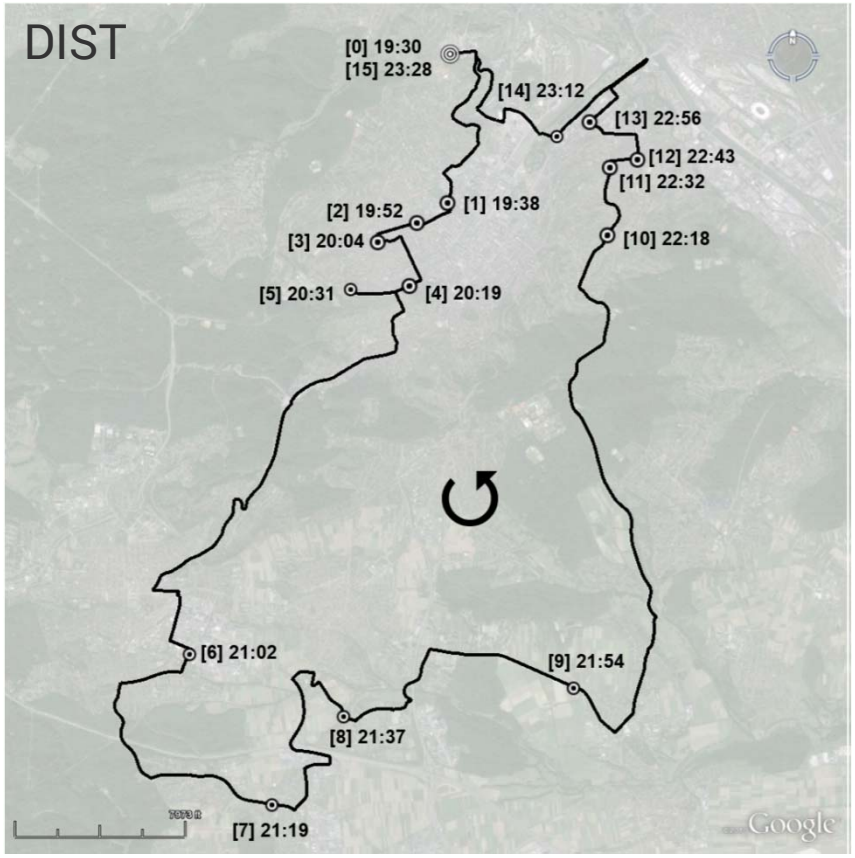
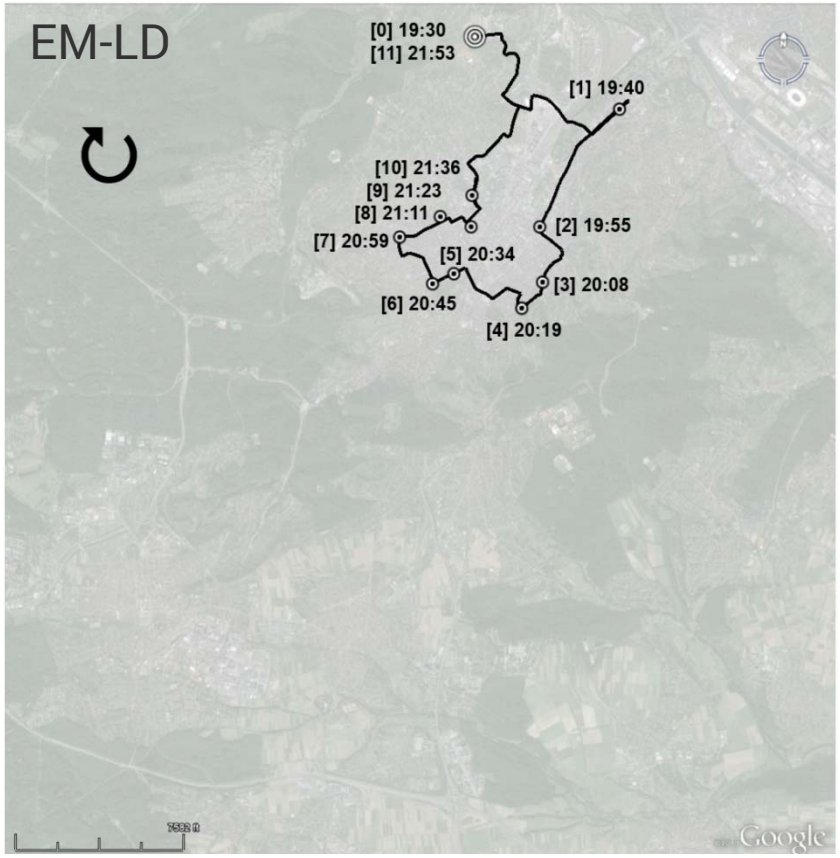
Examples for Heterogeneous Fleet, 15 Closest Heavy (Heavy Vehicle only)





- Highest savings with mixed fleet and heterogeneous customers
- Mixed instances/closest 15 heavy: savings in emissions of 10.25% vs. DIST routes

Summary and Outlook

- It is important to consider **dynamics of urban traffic** in transportation optimization
- Finding the **right level of aggregation** is crucial for run time and quality of solutions
- Smart ideas of **incorporating real data into optimization** can help making planning of routing more efficient, reliable and sustainable
- Consider more realistic **customer behavior**, different **emissions models** and more efficient ways of including **detailed traffic and customer data** into optimization

Thank you for your attention!

Further reading:

Jun.-Prof. Dr. Jan Fabian Ehmke

Advanced Business Analytics Group
School of Business & Economics

Freie Universität Berlin
Garystr. 21
D-14195 Berlin

☎: +49 (0)30 838-58731
@: janfabian.ehmke@fu-berlin.de
💻: www.wiwiss.fu-berlin.de/ehmke

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