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Modeling and Controlling Autonomous Transportation Systems in Smart Cities

Master Thesis

Brodo Luca

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Traffic Management is Necessary

As vehicle ownership increases, so do traffic inefficiencies.

- Increased congestions $\rightarrow$ toll on the economy (1% GDP of US ([1]))
- Increase consumption and pollution (60% of CO_2 emissions in the EU ([2]))
- Elevated risk for travellers' safety

Personalized and Shared Mobility as a solution

Some notable directions, such as

- Car Sharing (e.g. Car2Go)
- Mobility-as-a-Service (Maas) ([3])
- Autonomous Mobility on Demand (AMoD) ([4], [5])

  Key idea $\Rightarrow$ Holistic control over the vehicle's fleet

$\rightarrow$ Next step : Autonomous Transportation Systems (ATSs)

ATSs: The next step

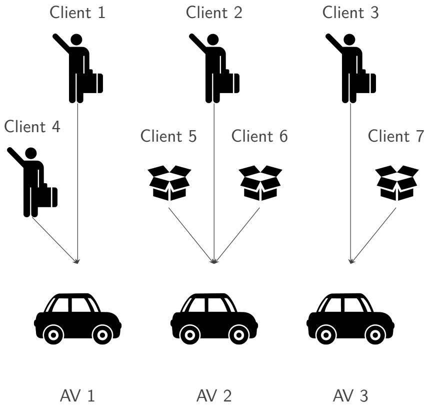
Extend the concept of personalized and shared mobility to goods delivery.
Three main pillars

- Minimized environmental impact and operational costs
- Ensured optimal quality of service (QoS), traffic control and road usage
- Tailorable solution

$\rightarrow$ What needs to be solved?

Tackling 4 Main Challenges

- **AV Dispatching**
- AV Routing
- AV Rebalancing
- Ride-Sharing and Delivery Pooling



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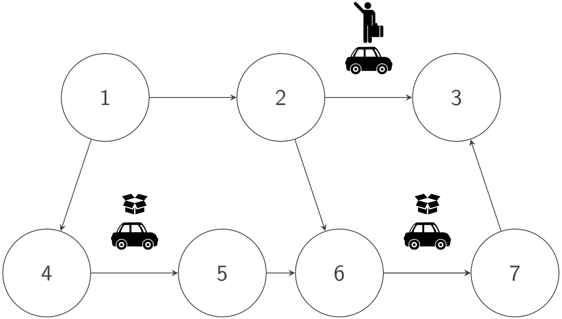

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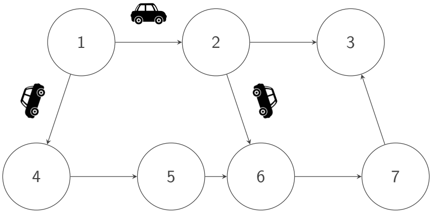

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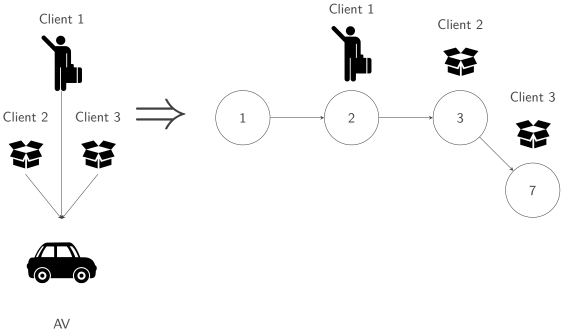
Tackling 4 Main Challenges

- AV Dispatching
- AV Routing
- AV Rebalancing
- **Ride-Sharing and Delivery Pooling**



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How to tackle them?

By observing what we have.

- Road Network
- Vehicles
- Requests

$\rightarrow$ Creating a vehicle-centric model of the ATS to solve the challenges.

Modeling the Road Network

Using a uni-directed graph $\mathcal{G} = \langle \mathcal{V}, \mathcal{E} \rangle$, where $\mathcal{V}$ represents the set of vertices (locations) and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ represents the edges (roads).

- Each edge is associated with multiple metrics (e.g., distance $d : \mathcal{E} \rightarrow \mathbb{R}_{\geq 0}$).
  $\Rightarrow$ Artificial limit on number of vehicles at each time
- Nodes can be of two types: charging ($\mathcal{V}_c$) and normal ($\mathcal{V}_n$) nodes.
- Charging nodes using ad-hoc charging profile models.

Modeling AVs

Each vehicle $a \in \mathcal{A}$ having:

- Starting and terminating nodes $\underline{s_a}$ and $\bar{t_a}$
- State of Charge $B_a \in \mathbb{R}_{>0}$ at time t
- Goods and people capacity $G_a \in \mathbb{R}_{\geq 0}$ and $P_a \in \mathbb{R}_{\geq 0}$
- Operational cost $C_a \in \mathbb{R}_{>0}$
- Pollution factor $F_a \in \mathbb{R}_{>0}$
- Set of assigned requests $\mathcal{R}_a$

Modeling Requests

Requests are modeled according to

- Pick-up and drop-off nodes $\underline{s}' \in \mathcal{V}_n$ and $\bar{t}' \in \mathcal{V}_n$
- Transportation demands for goods and people $G' \in \mathbb{R}_{\geq 0}$ $P' \in \mathbb{R}_{\geq 0}$
- Deterministic arrival rate $\lambda \in \mathbb{R}_{>0}$
- Time window $[a', b']$

The Complete ATS Management Problem

Combine the three models to

- Maximize number of served requests
- Reduce travel time (and pollution)

while

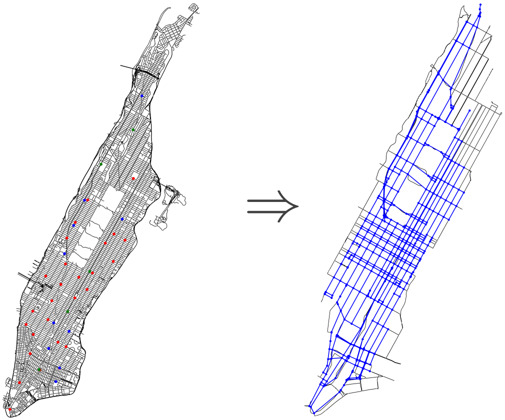
- Respecting deadlines
- Observing vehicle's characteristics (e.g., charge, cost and capacity)
- Eliminating congestions $\rightarrow$ artificial limit c on vehicles per road.

$\rightarrow$ Naturally an optimization problem.

Simulating the CATSM in Real-World

Using real-world data from NYC

- Geo-limited
- Large road network ($|\mathcal{V}| = 500$, $|\mathcal{E}| = 1700$)
- Deterministic λs



Evaluation

Promising results, but interrogatives are left open.

+ Solves all the challenges
+ Reduced computation thanks to a clever rebalancing formulation
+ Flexible and Modular model

- Congestion model is highly simplified
- Suffers large networks
- Does not gain insights on the future

How can the CATSM shortcomings be solved?

Three combined approaches

- Novel linear discrete-time model
- Definition of an ad-hoc model predictive control (MPC)
- Adaptive road network optimization using graph transformation systems (GTS)

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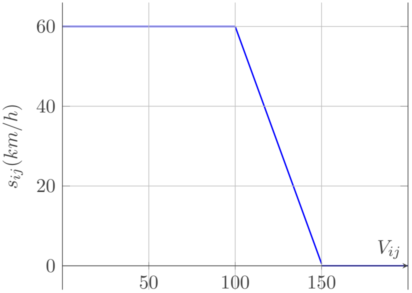
Novel Model for ATSs

Key idea $\rightarrow$ Define AVs speed in function of the number of AVs currently on the street

$$s_{ij}(V_{ij}) = \begin{cases} l_{ij} & \text{if } V_{ij} \in [0, V_{ij}^{th}) \\ l_{ij} - b \cdot (V_{ij}^{th} - V_{ij}) & \text{if } V_{ij} \in [V_{ij}^{th}, V_{ij}^{max}) \\ 0 & \text{if } V_{ij} \geq V_{ij}^{max} \end{cases}$$

with $b = \dfrac{l_{ij} - \epsilon}{V_{ij}^{th} - V_{ij}^{max}}$ and $\epsilon \in (0,1)$

$\rightarrow$ Implicitely, a better congestion model



$l_{ij} = 60km/h, V_{ij}^{th} = 100, V_{ij}^{max} = 150$ and $\epsilon = 0.5$

Novel Model for ATSs

As a result, new model linear time-discrete model can be defined, which tracks

- AVs' position using the speed
- Stationed AVs
- Served and Unserved requests using travelling vehicles

$\rightarrow$ System can be controlled by determining number of vehicles circulating

Model Predictive Control for ATSs

Let $\mathcal{X}$ and $\mathcal{U}$ being the set of feasible states and inputs, respectively, solve

$$
\begin{aligned}
\min_{u(t),\dots,u(t+N)} \quad & J_f(x(N)) + \sum_{t=0}^{N-1} I(x(t)) \\
\text{s.t.} \quad & x(t+1) = Ax(t) + Bu(t) \\
& x(t) \in \mathcal{X},\ u(t) \in \mathcal{U} \\
& x(N) \in \mathcal{X}_f
\end{aligned}
\tag{1}
$$

$\rightarrow$ Lyapunov stability can be proven

Model Predictive Control for ATSs

New control strategy possible which

- Reduces number of outstanding requests
- Minimizes unnecessary rebalancing vehicles

} Combined give $I(x(t))$

- Avoids transportation after requests are served
- Avoids rebalancing after requests are served

} Combined give $J_f(x(N))$

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Reduced Connectivity Schema

So far

- More sophisticated congestion model ✓
- Gained insights into the future of the system ✓

→ What about scalability?

Solution: Reduced Connectivity Schema (RCS).

In a nutshell, create a condensed version of G using a sequence of transformation rules $\mathcal{T}$.

Constructing an RCS

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Rules that have been applie

1. Restoration of important nodes' immidiate connections
2. Restoration of simpe nodes' immidiate connections (iteratively)
3. Straight Line Node elimination
4. Dead-End Removal

→ Depending on rule 2, the RCS may comprise as little as 18% of the original road network's size.

Evaluation

Good basis that can be further expanded

+ More descriptive model
+ Optimal control law guaranteed
+ Can "predict" the future

- The model is not tracking non-driving entities (e.g., pedestrians, cyclists)
- Special vehicles not considered (e.g., ambulances)
- Must be expanded further

Summary and Outlook

On the one hand, promising fundations have been layed down

- Holistic model for an ATS leading to a complete solution of its challenges
- Modular, adaptable and efficient linear model for real-time application
- Definition of a stable MPC for optimal control
- Novel complexity-reduction technique proposed for the road-network representation

On the other, multiple research directions have been opened:

- GTS must be further explored for more applications
- More sophisticated (non-linear) models are required for real world applications.
- What about safety insurance?

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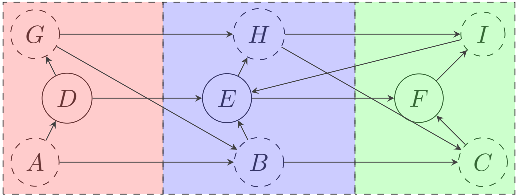
Leveraging the Request Model

Requests are key to solve the rebalancing problem

- Exploiting the deterministic λ
- Division in regions around depots, i.e. $\mathcal{G}_v = \langle \mathcal{V}'_v, \mathcal{E}'_v \rangle$
- Rebalancing becomes fundamentally an assignment problem



$$\mathcal{R}'_v = \{r \in \mathcal{R} : \underline{s_r}' \in \mathcal{V}'_v\}$$

Evaluating the MPC performance

	No RCS		RCS
	1	2	3
AVs #	30	-	-
Horizon (h)	3	-	-
Threshold (km/h)	60	-	-
Requests	240	-	-
Road (km)	30	R	-

	No RCS		RCS
	1	2	3
ATT (%)	33	36	3
ART (%)	17	14	3
Required AVs	19	12	10
Carrying AVs	13	11	4
Rebalancing AVs	11	12	9

System's Performance in a Nutshell

	w/o Rouing		w/ Routing	
	Sim. 1	Sim. 2	Sim. 1	Sim. 2
Total Distance (m)	731993	749006	806280	874937
Average Distance (m)	30500	312089	33595	36456
Total Time (s)	14640	14980	16126	17499
Average Time (s)	610	624	672	729
Unique Road Used	1171	1137	1193	1206
Request Served (%)	64	63	81	78

Evaluating the MPC performance