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University of Applied Sciences and Arts

Modeling and Controlling Autonomous Transportation Systems in Smart Cities

Master Thesis

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- Why Autonomous Transportation Systems?
- Addressing Key Challenges of ATS
- Modeling and Managing ATSs - The CATSM Problem
- Modeling and Controlling ATSs - The MPC for ATS and the RCS

Where are we Today?

Cars and small trucks have dominated transportation in the last century

- Inefficient use of the infrastructure
- Responsible for 60% of CO_2 emissions in the EU ([1])
- No more sustainable

Traffic Management is Necessary

As vehicle ownsership increases, so do traffic inefficiencies.

- Increased congestions $\rightarrow$ toll on the economy (1% GDP of US ([2]))
- Increase consumption and pollution
- Elevated risk of accidents

ATSs Solve These Problems

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

- Ensured optimal quality of service (QoS)
- Optimized traffic control and road usage
- Minimized environment impact and operational costs

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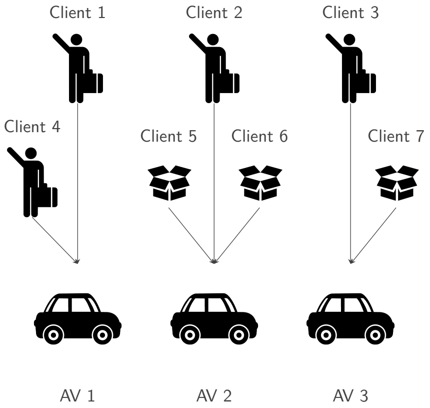
Tackling 4 Main Challenges

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



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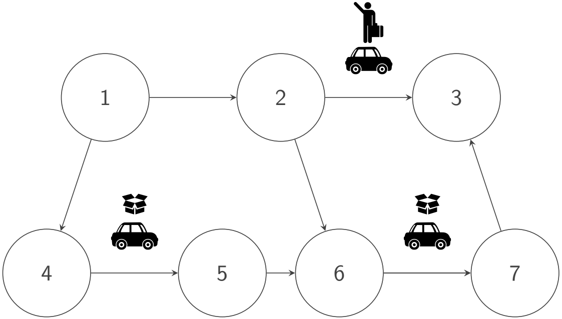

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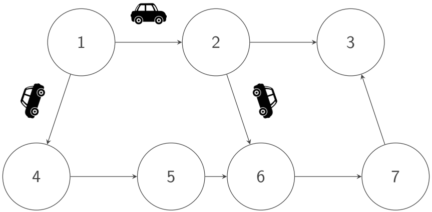

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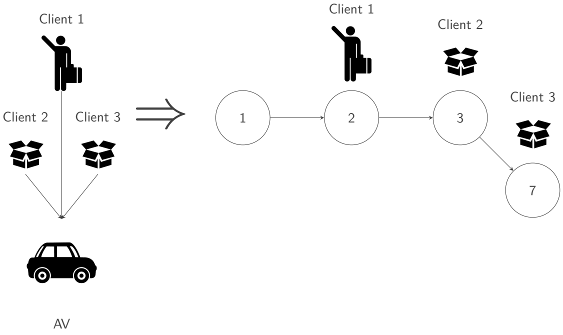

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How can ATSs be Modeled?

Three main elements to model

- Road Network
- Vehicles
- Requests

$\rightarrow$ Forming a vehicle-centric model of the ATS

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Modeling the Road Network

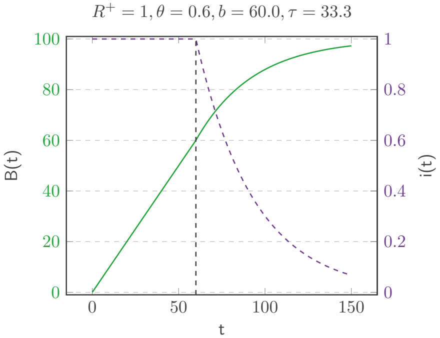
Using a irect graph $\mathcal{G} = \langle \mathcal{V}, \mathcal{E} \rangle$, where $\mathcal{V}$ is the set of vertices (Locations) and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ the edges (Roads)

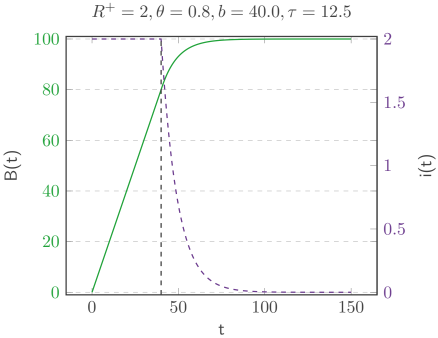
- Each edge associated with multiple metrics (e.g. distance $d : \mathcal{E} \to \mathbb{R}_{\geq 0}$)
- Nodes can be of two types, charging ($\mathcal{V}_c$) and normal ($\mathcal{V}_n$) nodes
- Charging nodes with different charging profiles

Forming a vehicle-centric model of the ATS

Charging Profiles

AV batteries modeled using the CC-CV (Constant current - Constant Voltage) scheme.
Modeled as tuple $\mathcal{T}_a = \langle Q_a, I_a^b, R_a^-, R_a^+, \theta_a \rangle$.





Modeling AVs

Each vehicle $a \in \mathcal{A}$ as a tuple $\langle \underline{s_a}, \bar{t_a}, B_a(t), \mathcal{R}_a, \mathcal{T}_a, P_a, G_a, C_a, F_a \rangle$.

- Starting and terminating depot $\underline{s_a}$ 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 $F_a \in \mathbb{R}_{>0}$
- A battery $\mathcal{T}_a$
- Set of assigned requests $\mathcal{R}_a$

Modeling Requests

Requests are modeled as tuples $\langle \underline{s'}, \bar{t'}, G', P', \lambda, a', b' \rangle$

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

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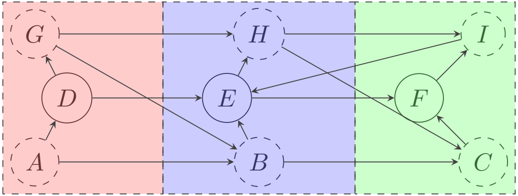
Leveraging the Request Model

Requests are key to solve the rebalancing problem

- Exploiting 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



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

The Complete ATS Management Problem

In a nutshell, maximize number of served requests and minimize vehicle's travel time, while

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

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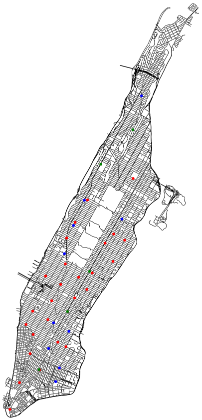
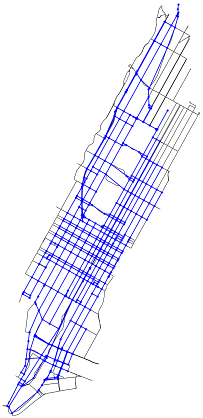
Simulating the CATSM in Real-World

Using real-world data from NYC

- Simplified, yet large road network ($|\mathcal{V}| = 500$, $|\mathcal{E}| = 1700$)
- Fictitious depots' locations
- Deterministic requests rates



$\Rightarrow$



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

Evaluation

Promising results, but interrogatives are left open.

+ Solves all the ATSs challenges
+ Finds numerically optimal solutions
+ Is flexible and modular

- Congestions' model is highly simplified
- Suffers large networks
- Is not suitable for real-time
- Doesnt have possible insights on the future

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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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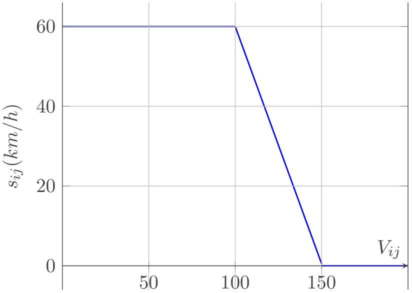
Novel Model for ATSs

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 Unrequests using travelling vehicles

$\rightarrow$ It's also easily controllable

MPC for ATSs

Let $V_{ij}(t) \in \{x \in \mathbb{N}_0 : x \leq |\mathcal{A}|\}$ being the total number of vehicles currently circulating on the street $\langle i, j \rangle$, this can be easily computed by adding the number of carries to the rebalancing AVs, i.e.

$$V_{ij}(t) = \sum_{a \in \mathcal{A}} v_{ij}^a(t) + w_{ij}^a(t)$$

$\rightarrow$ Control $v_{ij}^a(t)$ and $w_{ij}^a(t)$

MPC for ATSs

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

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

where $\mathcal{X}_f$ is the set of terminal states, $J_f(x(N))$ is the terminal cost function and $I(x(t))$ is the stage cost

MPC for ATSs

The main objectives are to:

- Reduce number of outstanding requests
- Minimize unnecessary rebalancing vehicles

Combined give $I(x(t))$

- Avoid transportation after requests are served
- Avoid rebalancing after requests are served

Combined give $J_f(x(N))$

$\rightarrow$ Stability can be proven

Reduced Connectivity Schema

As a result, a more sophisticated congestion model and insights on the impact of the decisions on the future have been acquired.What about real-time and scalability?

Solution: Reduced Connectivity Schema (RCS)
In a nutshell $\rightarrow$ Create a simplified version of G using a sequence of transformation rules $\mathcal{T}$.

Constructing an RCS

Rules are highly application-dependent, therefore let's assume the NYC road network used prior.

Examples of applied rules starting from only the important nodes

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

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

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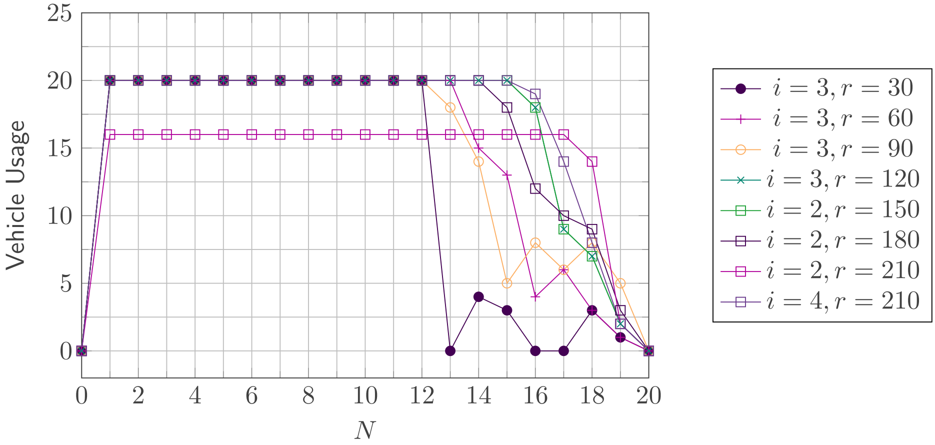
Evaluating the MPC performance

	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

Evaluating the MPC performance



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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
- Using the MPC to control real-world vehicles
- What about safety insurance?

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