An Optimal Control Framework for Reliable & Sustainable Bus Operation

GSC'25

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TECHNION SUSTAINABLE MOBILITY AND ROBUST TRANSPORTATION LABORATORY

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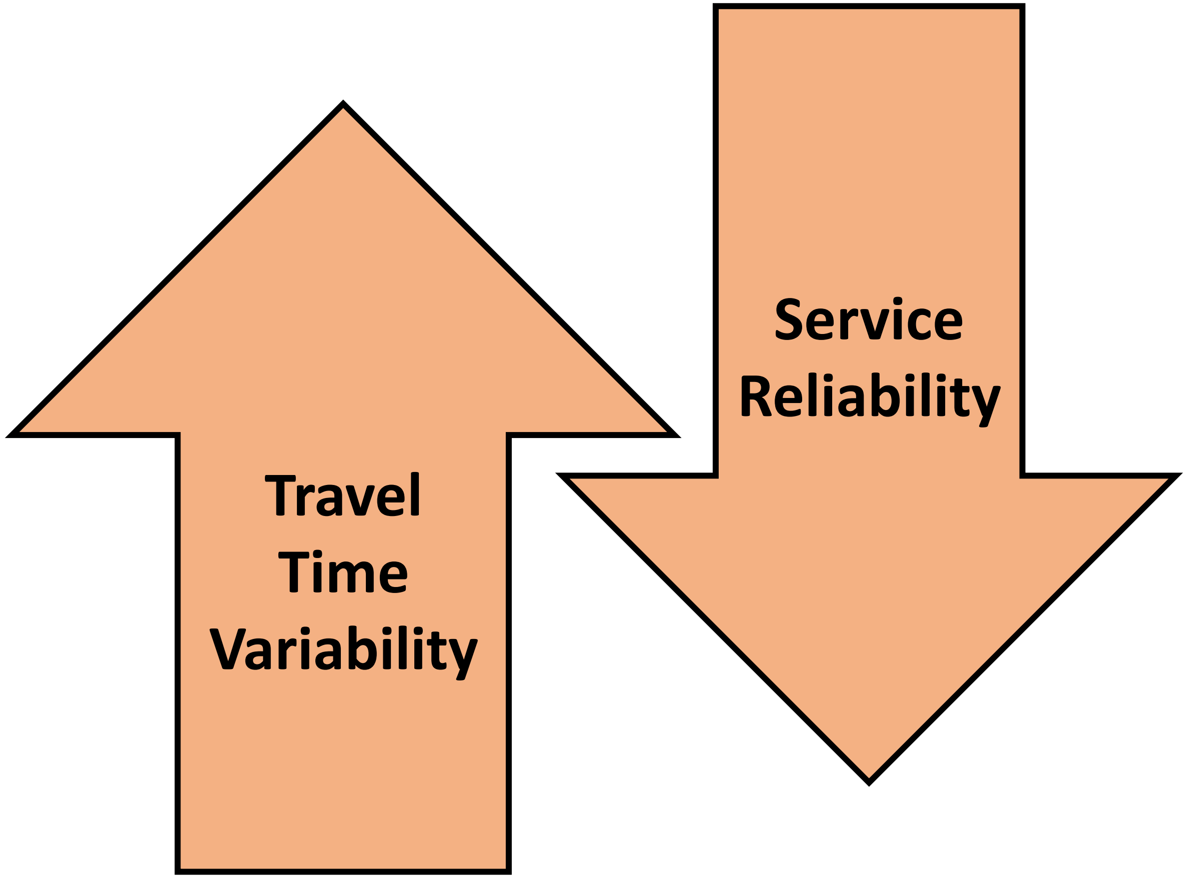
Agenda

- Motivation
- Methodology
- Case Studies
- Results
- Conclusion Remarks

Motivation

An optimal control framework for reliable and sustainable public transit operation



By Felix O - 55 Buses, Clapton Pond Uploaded by oxyman, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=10935479

Motivation

An optimal control framework for reliable and sustainable public transit operation

To provide an efficient and sustainable service

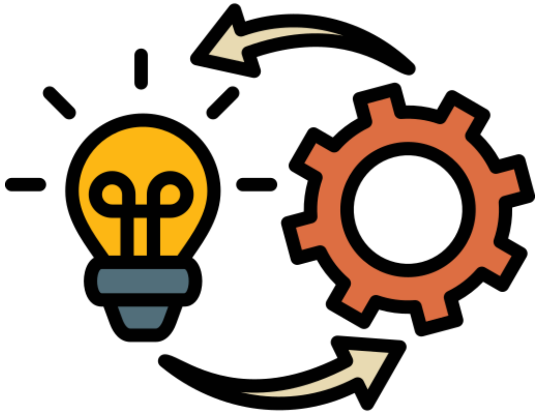
To deliver service as planned

Motivation

An optimal control framework for reliable and sustainable public transit operation

State of the art

The two objectives have been studied separately

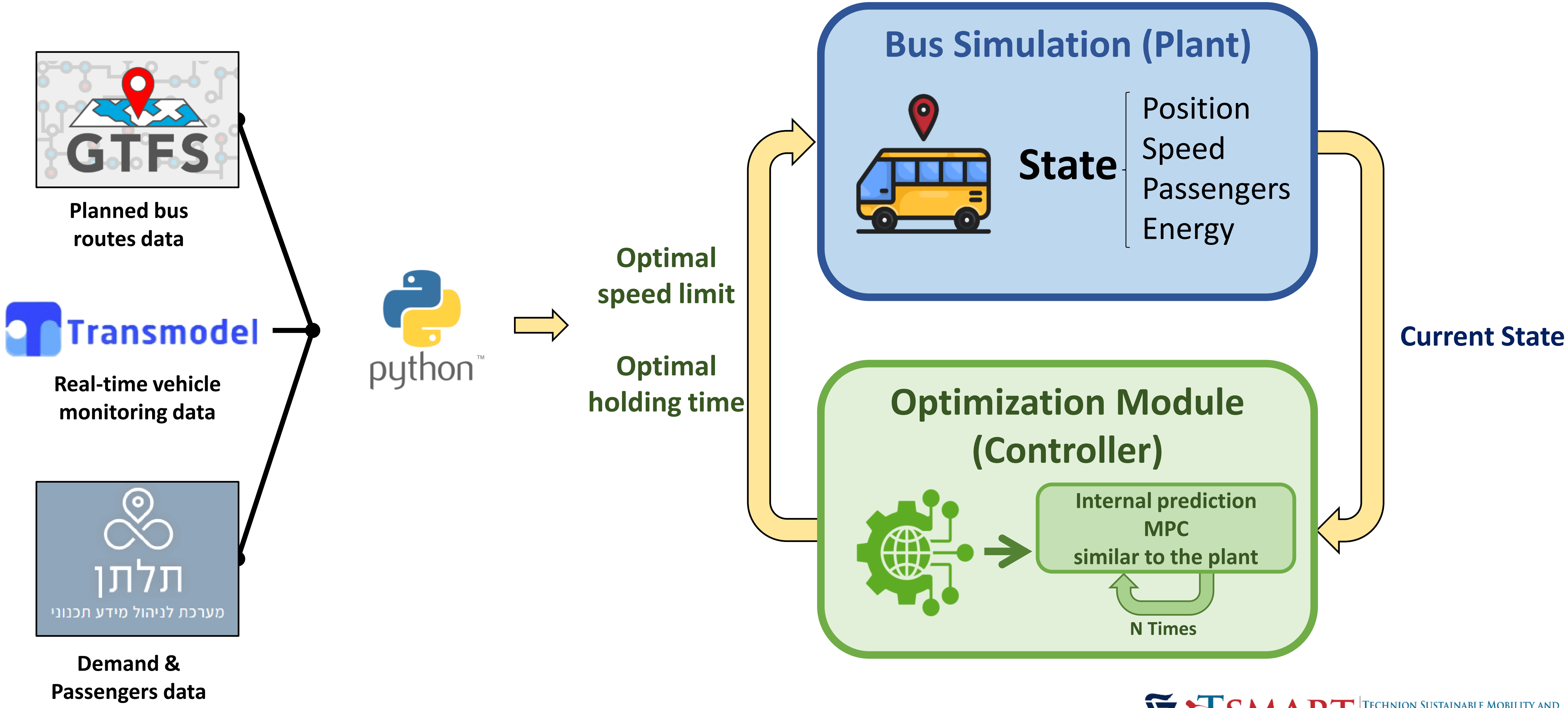


State of the Practice

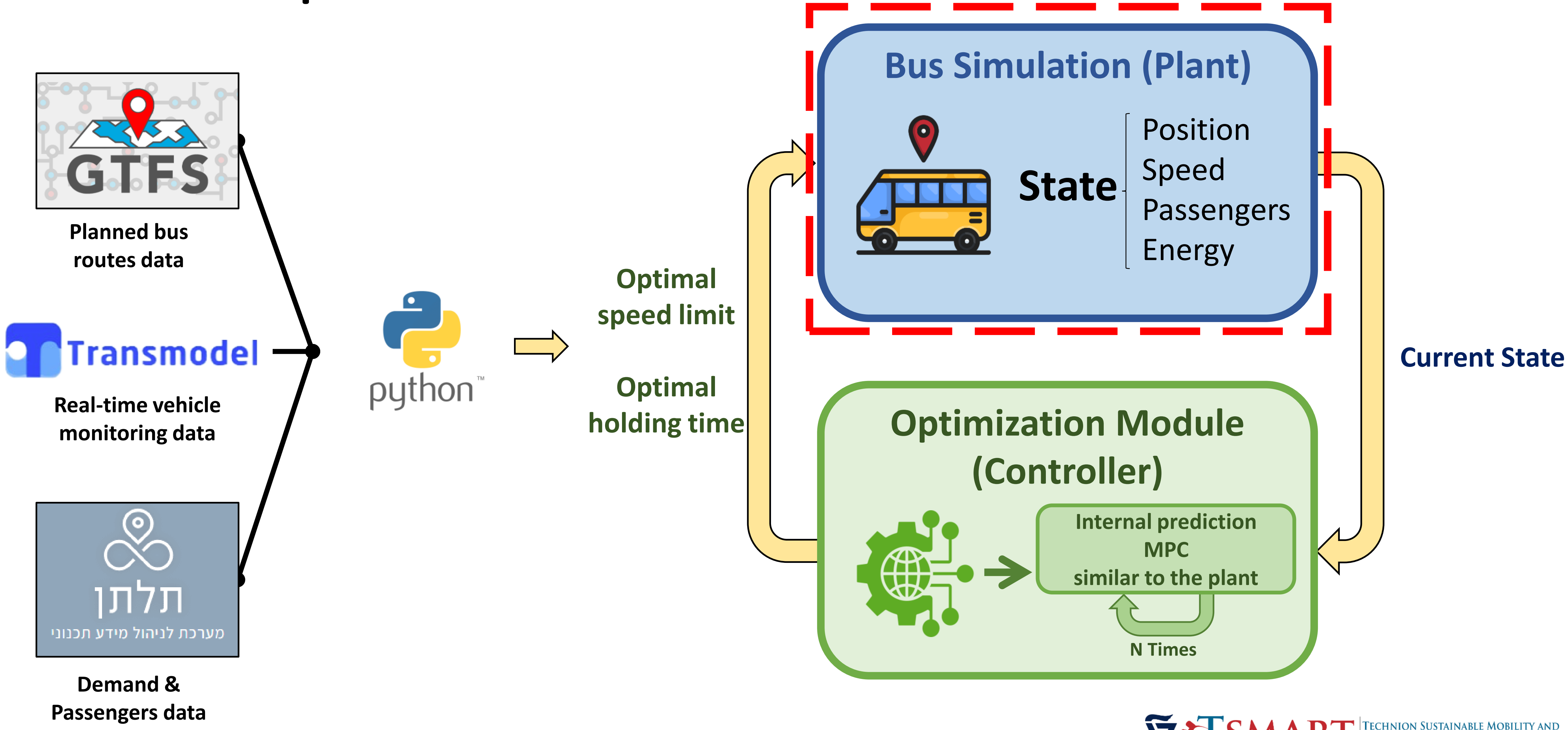
Initial approaches have seen limited implementation globally

Methodology

Developed Simulation Framework



Developed Simulation Framework



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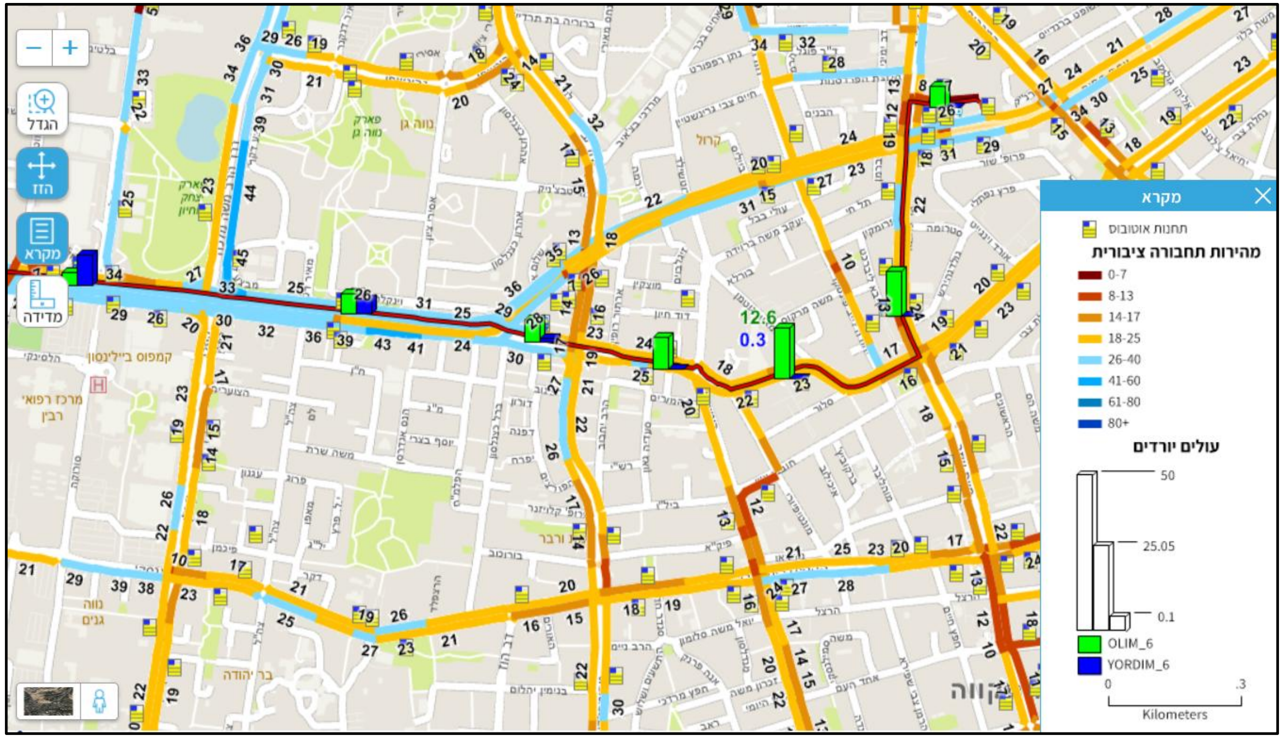
Bus Transport System Modeling

Simulating Traffic Conditions

Bus Simulation (Plant)

State:
- Position
- Speed
- Passengers
- Energy



https://tiltan.ayalonhw.co.il/tiltan/App.aspx

Deviations from historical average*

$$\sigma^2_{traffic} = 5\ m^2/s^2$$

↓

Traffic state is changed every 10 seconds

$$Traffic = \max(0, \min\left(SL, \mathcal{N}\left(avg.speed, \sigma^2_{traffic}\right)\right)$$

↓

Smoothing Factor*

$$\alpha = 0.2$$

↓

Actual bus speed

$$Speed(t) = \alpha \cdot Speed(t-1) + [1-\alpha] \cdot Traffic$$

**Calibrated using real TOM open-source public transit data – GTFS & SIRI-VM formats*

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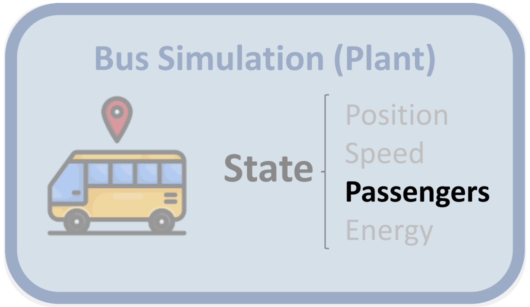
Bus Transport System Modeling

Simulating Passengers & Demand



Bus $\boldsymbol{i}$ passenger accumulation $\boldsymbol{n}$ at stop $\boldsymbol{s}$:

$$\boldsymbol{n_i^s = \lambda_i^s(t_i^s - t_{i+1}^s) + (1 - \mu_i^s) * n_i^{s-1}}$$

Bus i is expected to find $\boldsymbol{\lambda_i^s(t_i^s - t_{i+1}^s)}$ passengers, as $\boldsymbol{\lambda}$ varies at each stop following demand profile

$\mu_i^s \rightarrow$ alighting proportion at stop s following demand profile

$$0 \leq n_i^s \leq n_{\max}$$

$$0 \leq \mu_i^s \leq 1$$

$$0 \leq \lambda_i^s$$

Mass of bus i:

$$\boldsymbol{m_i(t) = m_{\text{emp}} + n_i(t) * m_{\text{pax}}}$$

$m_{\text{pax}} \rightarrow$ An average passenger mass [kg]

$$m_{\text{emp}} \leq m_i(t) \leq m_{\text{full}}$$

*Luethi, M., Weidmann, U., and Nash, A. (2007). Passenger arrival rates at public transport stations. InTRB 86th Annual Meeting Compendium of Papers, pages 07–0635. Transportation Research Board.

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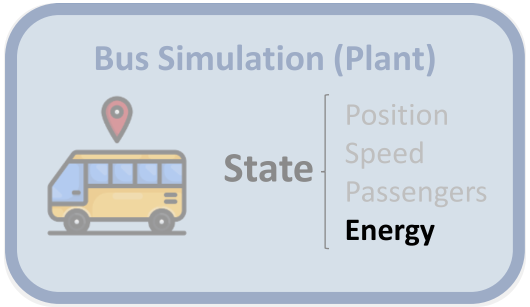
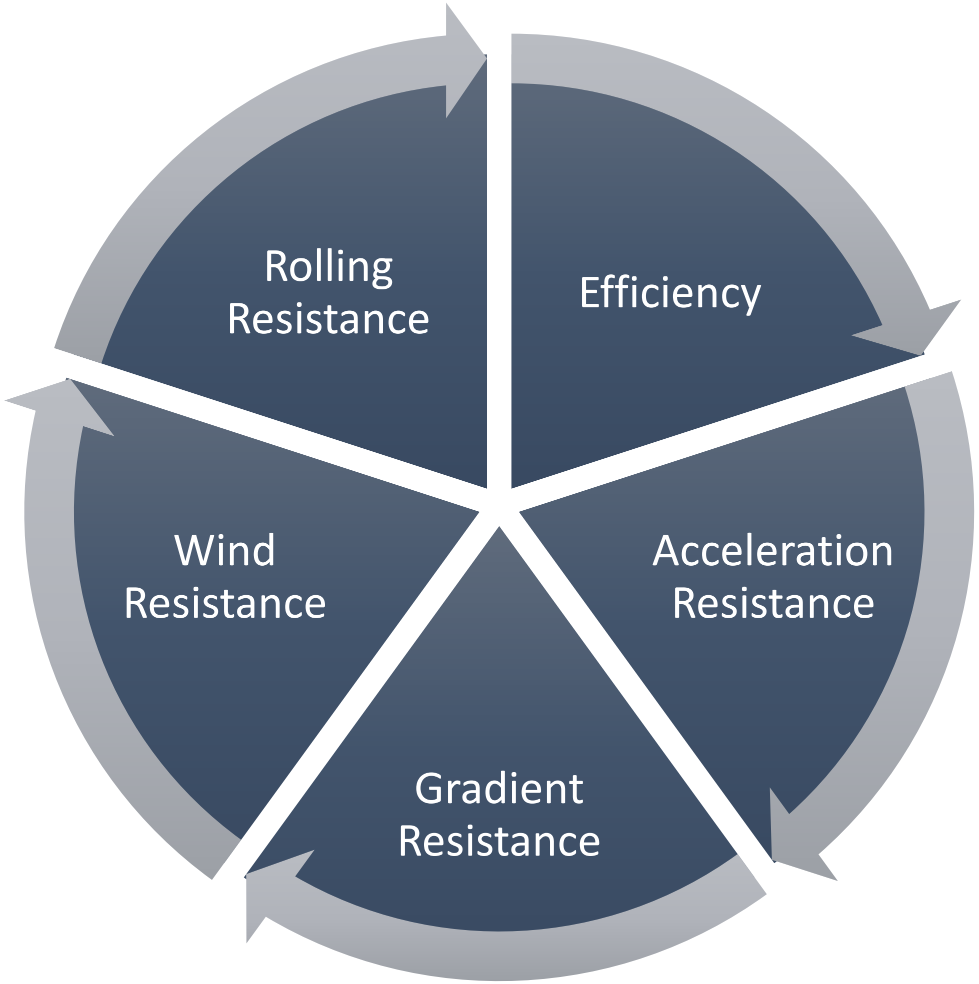
Energy Model





$$\boldsymbol{Power} \rightarrow P = \frac{v}{\eta_t} \cdot F_t = \frac{v}{\eta_t} \cdot \left(F_r + F_w + F_i + F_j\right) + \underbrace{v(t) * m(t) * a(t) * \eta_{KERS}}_{\text{Regenerative Braking}}$$

$$\boldsymbol{Energy} \rightarrow EC = \int_0^T P(t)dt \ [kWh]$$

η_t	*Total Efficiency*	
$\boldsymbol{F_r}$	*Rolling resistance*	$m_i(t) \cdot g \cdot C_{rr} \cdot \cos(\alpha)$
$\boldsymbol{F_w}$	*Air resistance & drag*	$\frac{1}{2} \rho \cdot A \cdot C_D \cdot v_i^2$
$\boldsymbol{F_i}$	*Gradient resistance*	$m_i(t) \cdot g \cdot \tan(\alpha)$
$\boldsymbol{F_j}$	*Acceleration resistance*	$m_i \cdot \frac{\partial v}{\partial t}$

Varga, Balázs, Tamás Tettamanti, and Balázs Kulcsár. "Energy-aware predictive control for electrified bus networks." *Applied Energy* 252 (2019): 113477.

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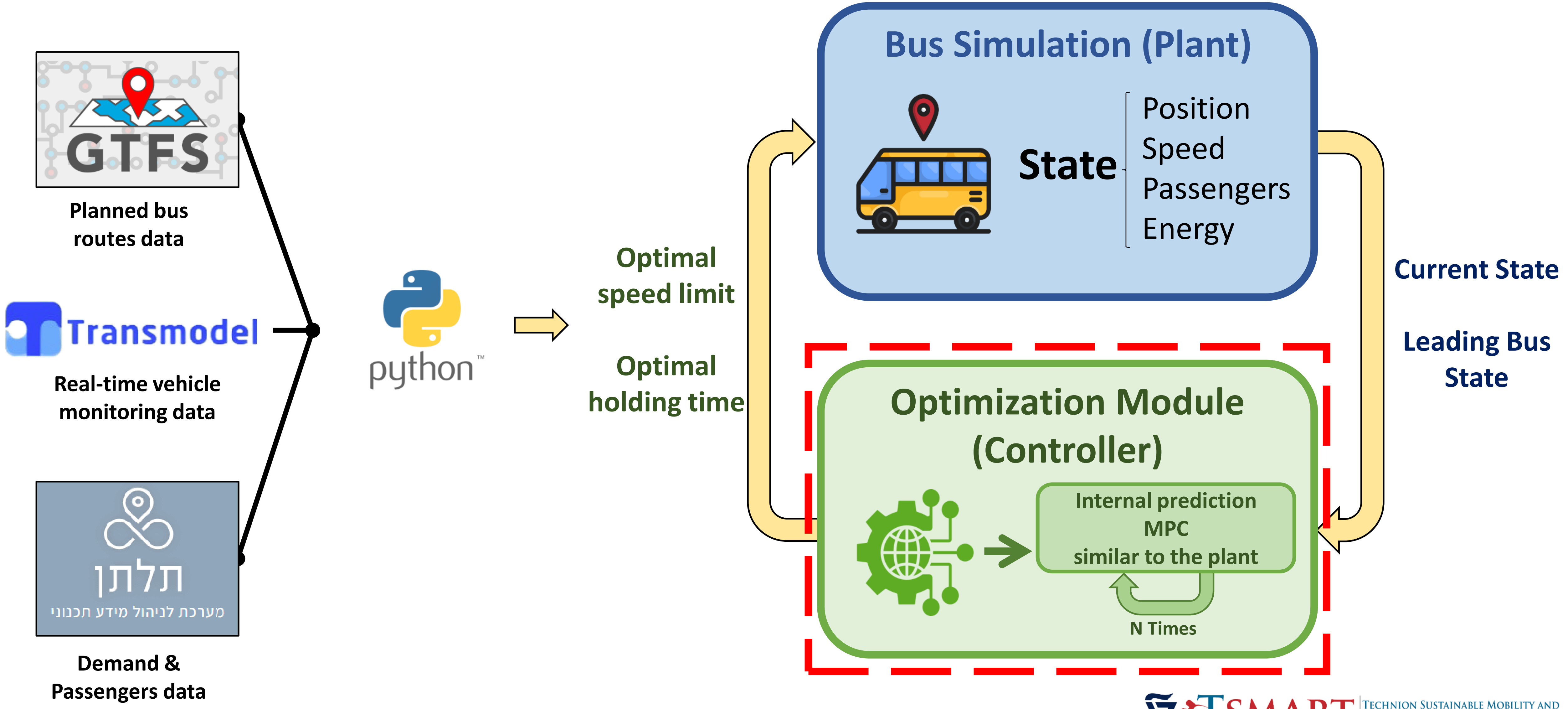
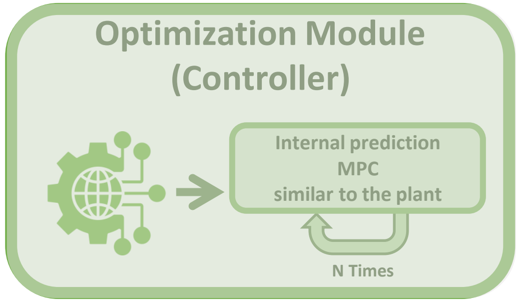
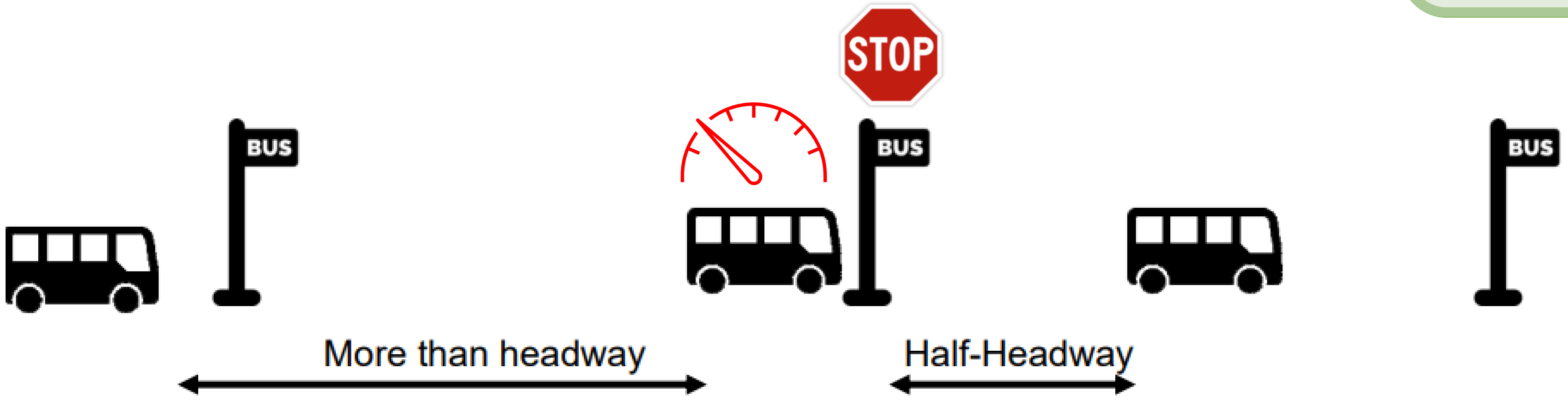
Developed Simulation Framework



Control System

Speed Limit & Holding Adjustments





<u>Control variables</u>

STOP u_h **Holding time** at the current stop

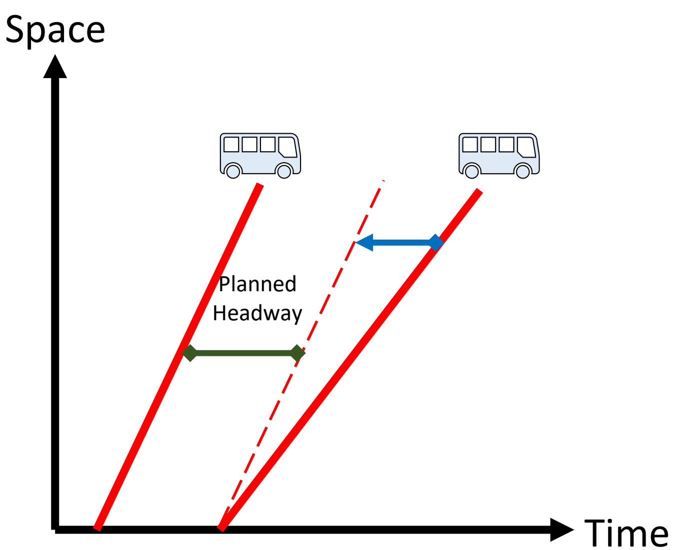
u_{SL} **Speed limit** for the next section

<u>State variables</u>

Position	Arrival times at stops	Passengers on board
Speed	Energy consumption	Demand profiles

⋮

And many others



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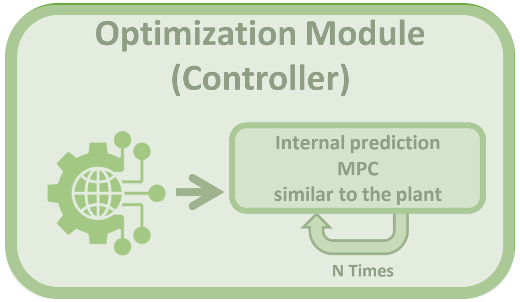
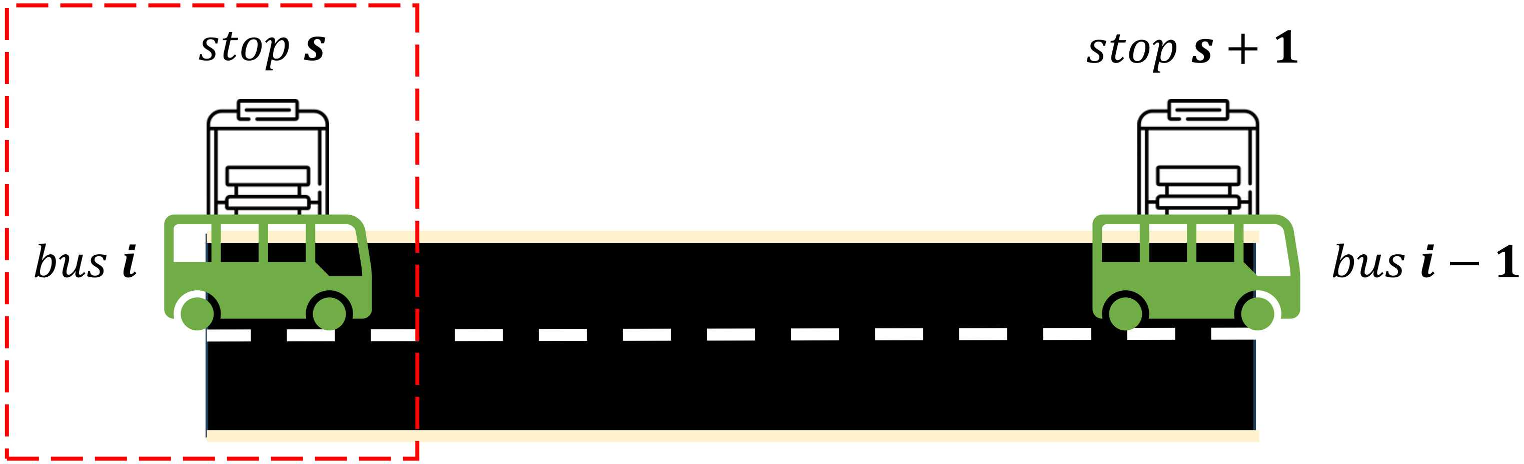


Optimal Control Framework

Event-based optimization occurs for bus i at each stop s



Headway Error ***Energy Consumption***

$$\min \sum_{i=1}^{n} \omega_1 \cdot \left(H_{\text{ref}} - H_{i-1,i}\right)^2 + \omega_2 \cdot EC$$

s.t.

$0 \le u_h(t) \le u_{h_{max}}$ ***Holding time constraint***

$0 \le u_{SL}(t) \le SL_{s,s+1}$ ***Speed Limit constraint***

⋮

All other state constraints

$\boldsymbol{H_{\text{ref}}}$
Planned headway

$\boldsymbol{H_{i-1,i}}$
Time gap between consecutive arrivals

Calibration

Weights are calibrated using the **Weighted Sum Approach**

Prediction

Decentralized **Model Predictive Control**

Optimization

SQP Algorithm Sequential Quadratic Programming

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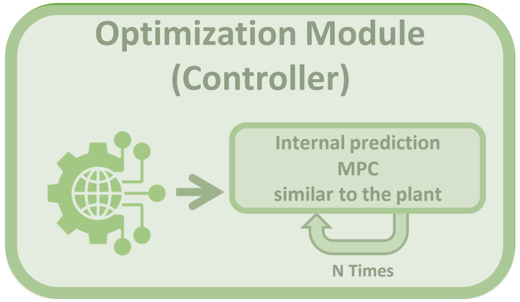
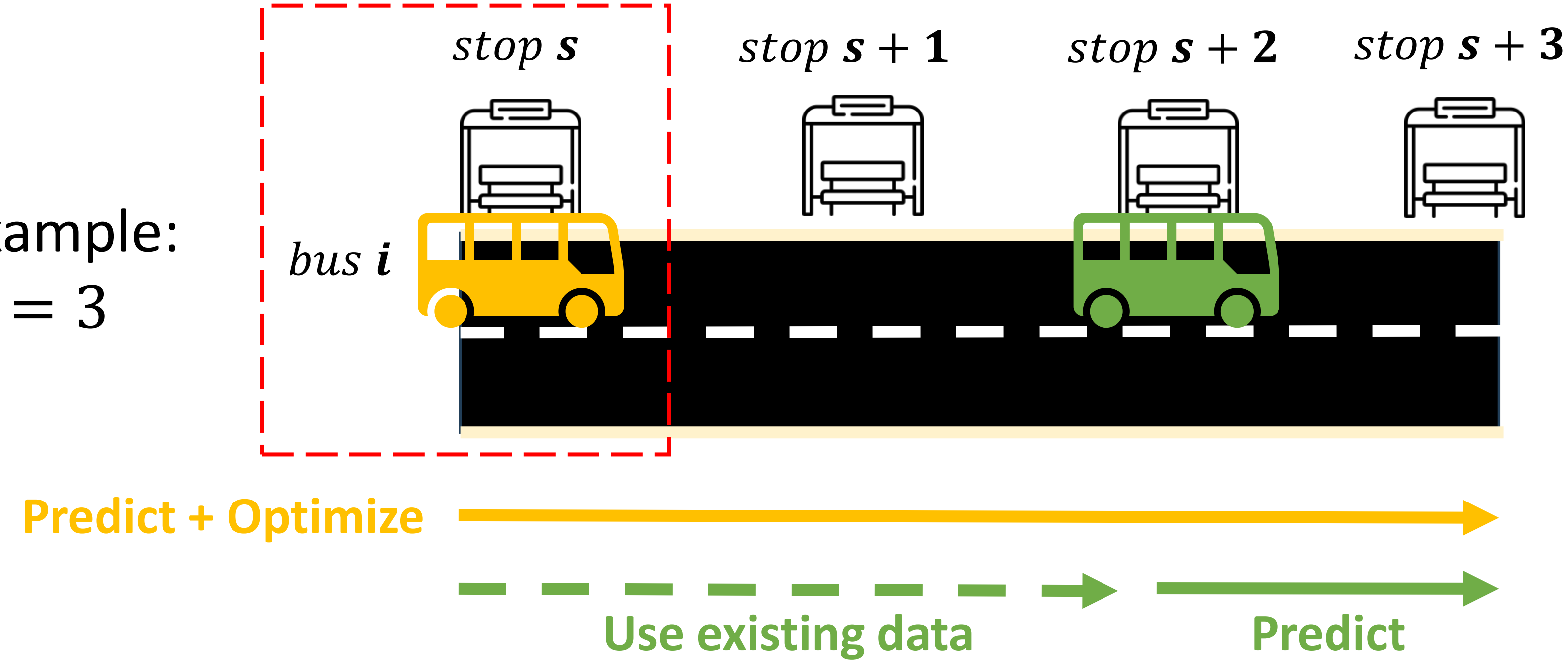
Optimal Control Framework

Decentralized Model Predictive Control



For example:
$N_P = 3$



Chosen Horizons	
Prediction horizon	$N_p = 2\ stops$
Control horizon	$N_c = 1\ stop$

Calibration

Weights are calibrated using the **Weighted Sum Approach**

Prediction

Decentralized **Model Predictive Control**

Optimization

SQP Algorithm
Sequential Quadratic Programming

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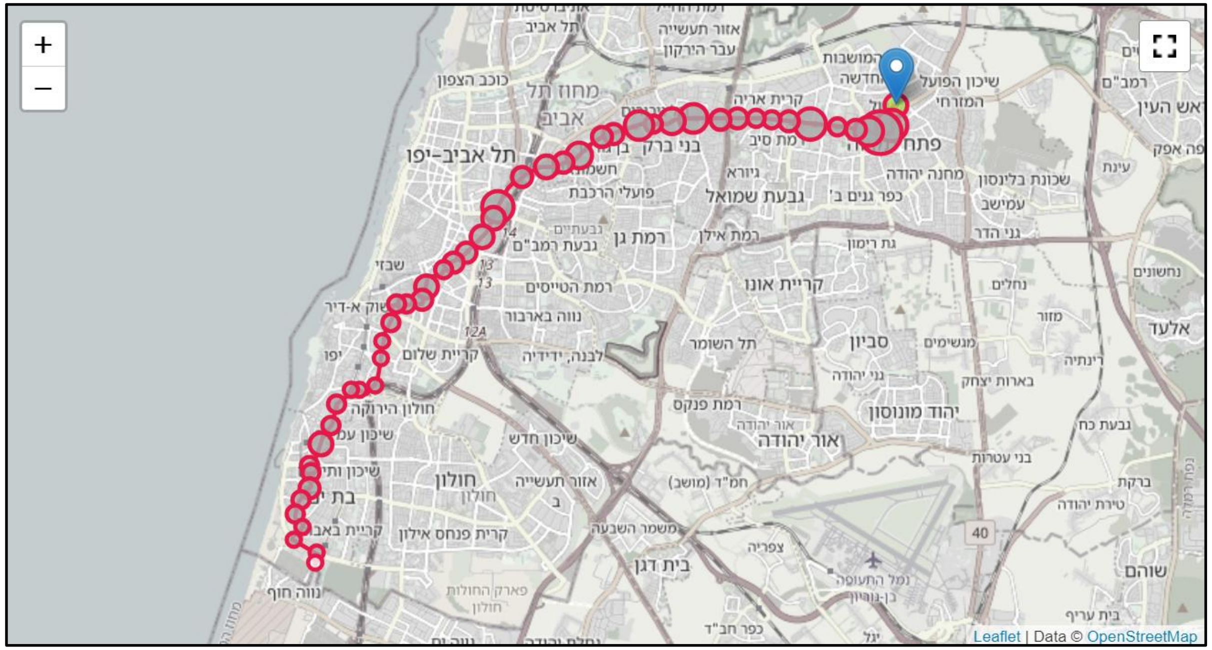
Case Studies & Results

Line 1 (81001) – Simulation

Bus Transport System Setting



*https://markav.net/line/81001/

Parameter	Numerical Value	Units
Route length	22,000	$[m]$
Number of buses	6	$[-]$
Number of stops	51	$[-]$
Bus headway	10	$[min]$
Speed boundaries	[0, 50]	$\left[\frac{km}{hr}\right]$
Acceleration boundaries	[-2, 1]	$\left[\frac{m}{s^2}\right]$
Passenger accumulation boundaries	[0, 80]	$[pax]$

Key Metric of Stability – Cvh

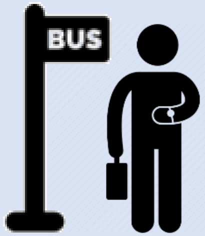
Coefficient of Variation of Headways

$$C_{vh} = \frac{\sigma_{Hd}}{H}$$

⇨ σ_{Hd} - Standard deviation of the deviations from the scheduled headway

⇨ H - Scheduled headway between two consecutive trips

Example



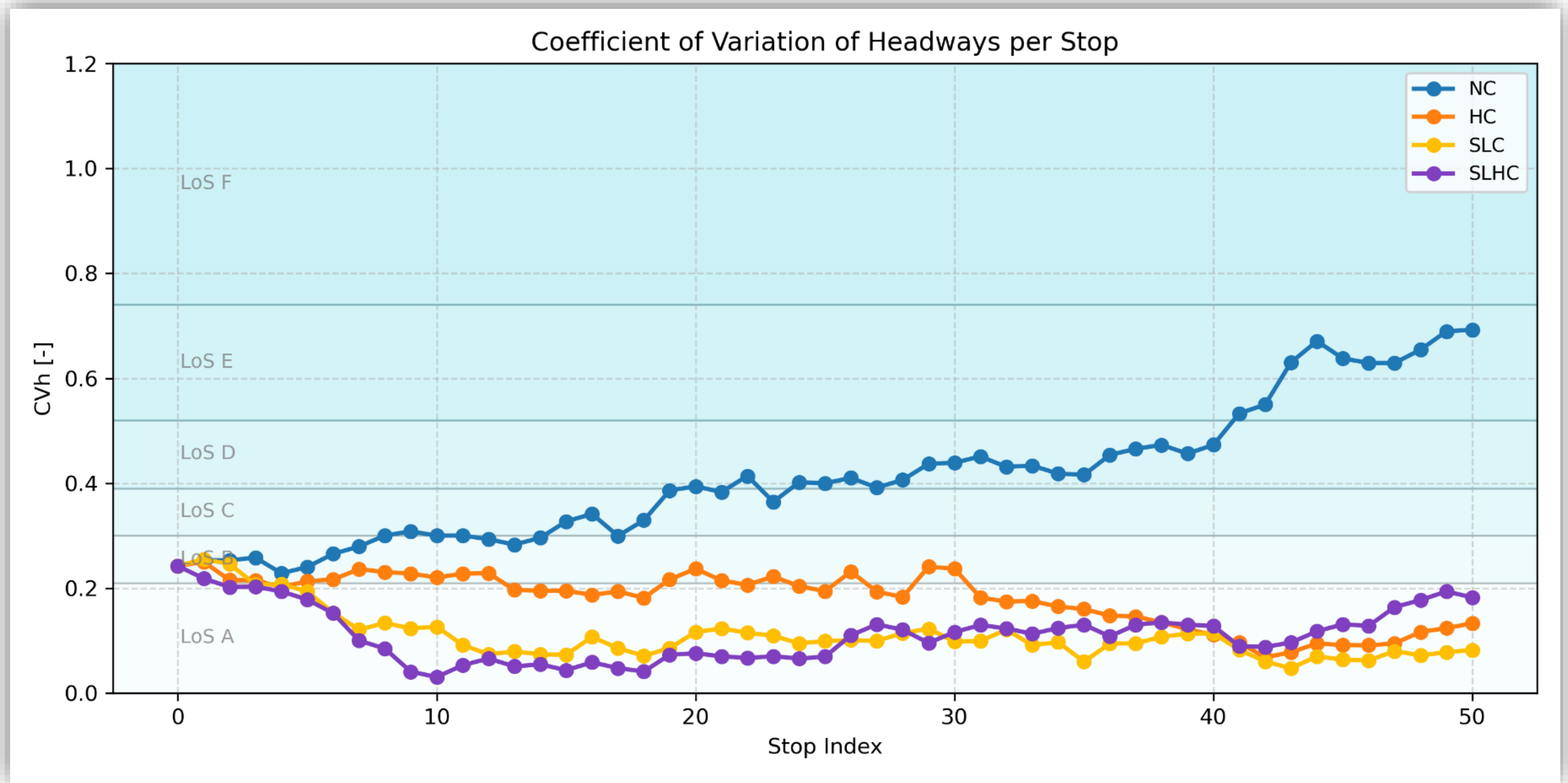
1. The scheduled headway of a certain line is every 10 minutes.
2. In practice, the measured headways at a certain stop are 12, 8, 14, 6, 13, 7.
3. Therefore, the deviations from the scheduled headway are +2, -2, +4, -4, +3, -3.
4. The standard deviation of the deviations from the headway is 3.4.
5. Hence, the value of the headway variance index is 0.34 and the level of service is “C” (Moderate)*.

**Transit Capacity and Quality of Service Manual, 3rd Edition*

Results – Line 1 (81001)

Moderate inconsistency in departures was examined

- **NC** – No Control
- **HC** – Holding Control
- **SLC** – Speed Limit Control
- **SLHC** – Speed Limit & Holding Control



$\boldsymbol{Cvh\ of\ Line\ 1\ -81001}$

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Results – Line 1 (81001)

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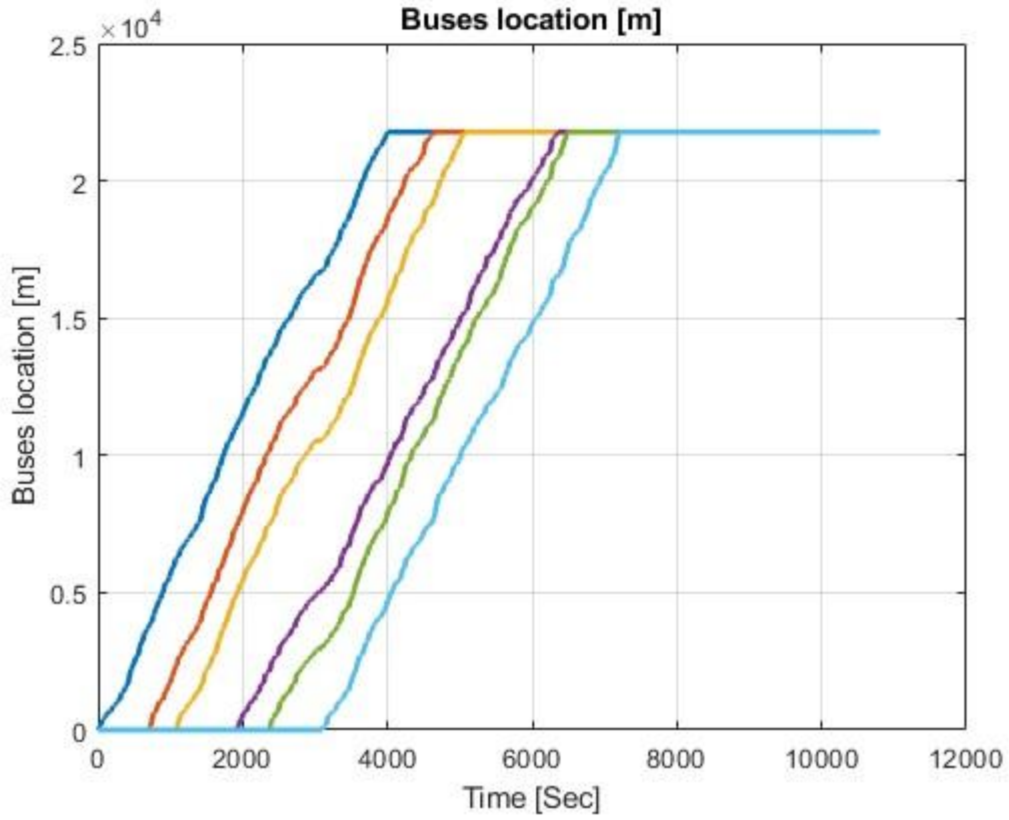
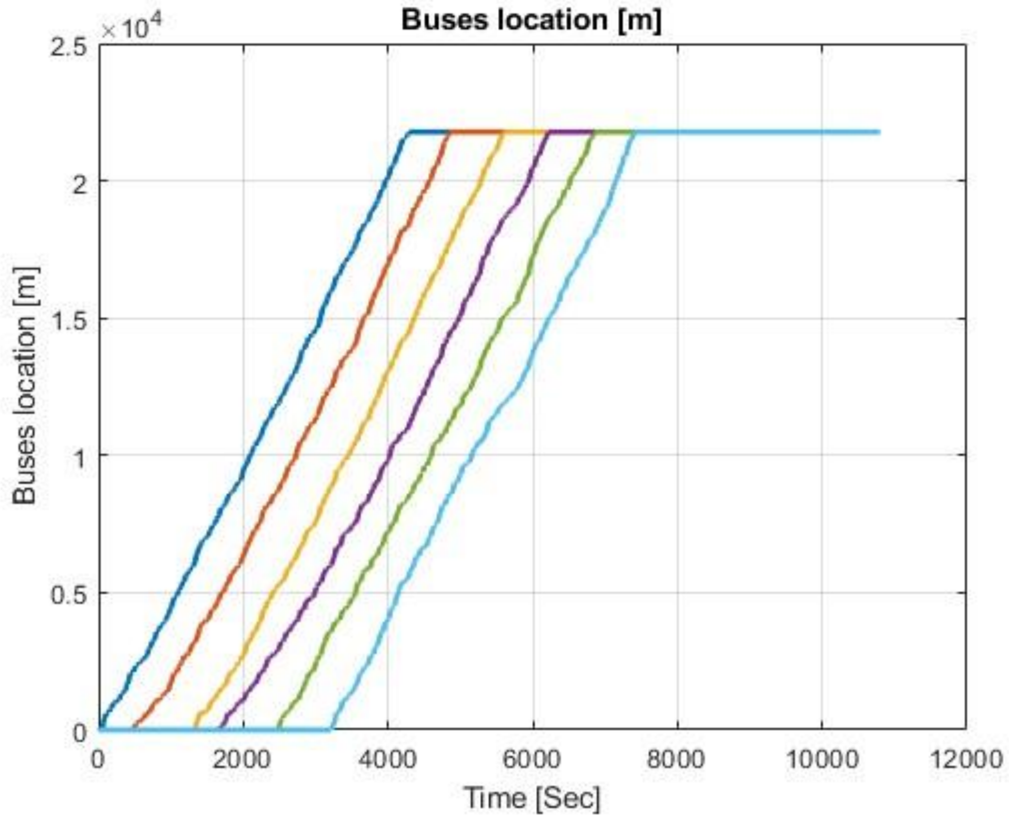




Examined Routes – Peak Hours [6-8 AM]

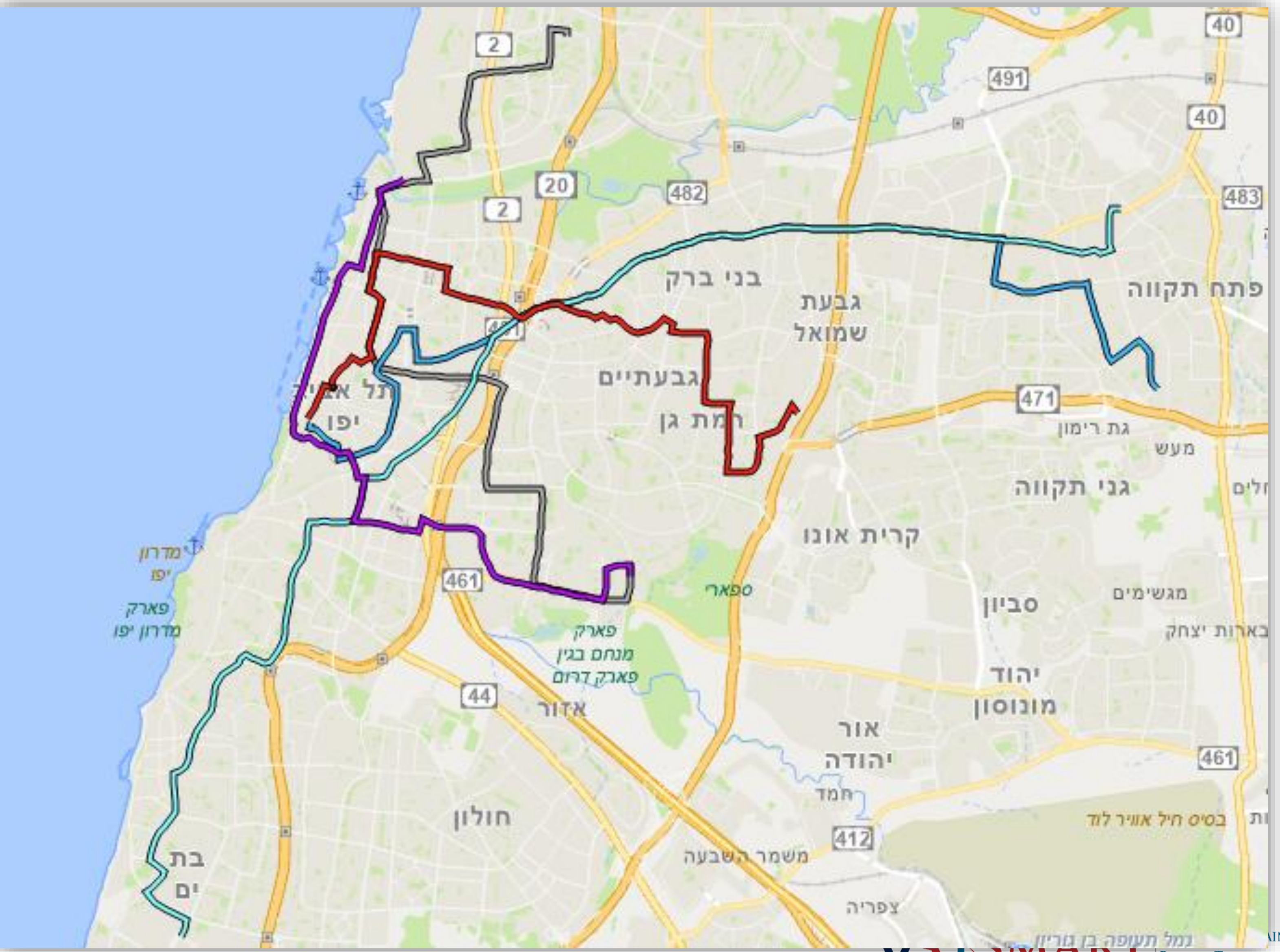
Route 1

Route 61

Route 8

Route 82

Route 4



https://tiltan.ayalonhw.co.il/tiltan/App.aspx

Examined Routes – Peak Hours [6-8 AM]

	Line no.	Frequency $\left[\frac{trips}{hr}\right]$	Route length $[km]$	Vehicle Type
81001	1	6	21.8	Articulated bus
16061	61	6	12.7	Urban bus
55008	8	8	14.7	Urban bus
29082	82	10	17.3	Urban bus
27004	4	10	11.8	Urban bus

High-frequency routes with heavy demand and significant traffic

Results

Moderate inconsistency in departures was examined

NC – No Control

HC – Holding Control

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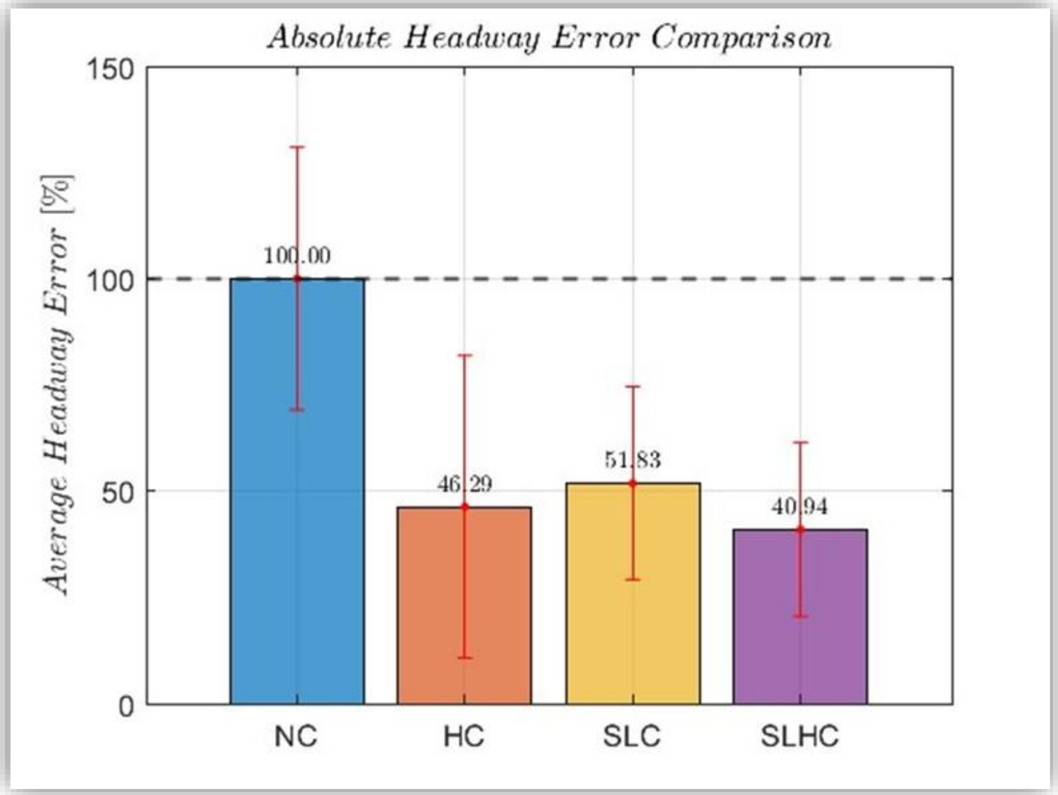
SLHC – Speed Limit & Holding Control



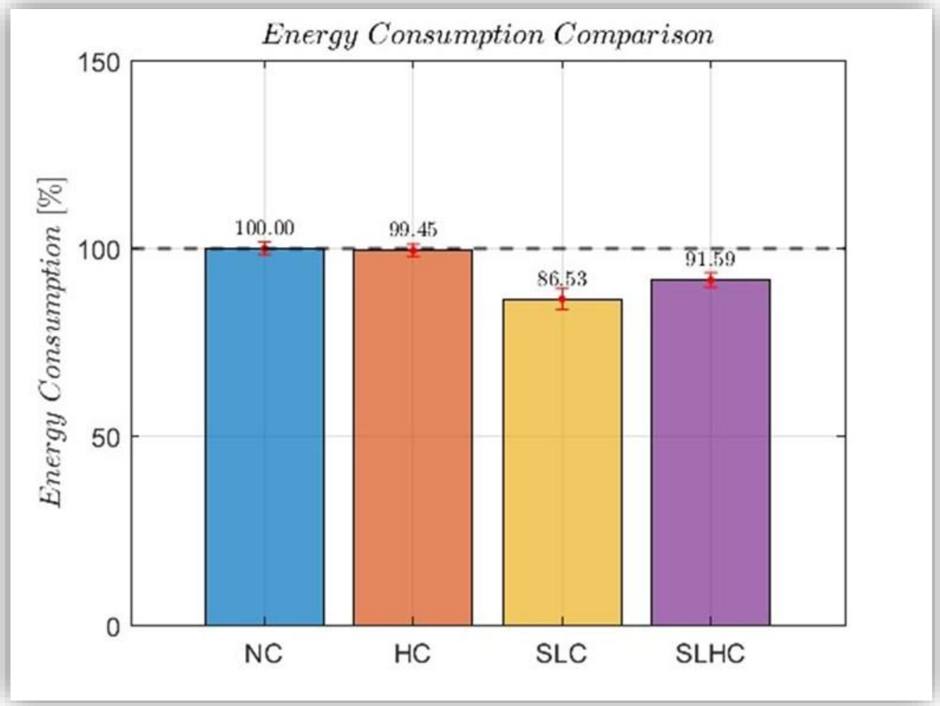
$\mathbf{60\%}$ *reductions in deviations from reference headway*

<u>Line 1 - For Example</u>:

Average HW error without control - **~250 seconds**

Average HW error with control - **~100 seconds**

Results



NC – No Control

HC – Holding Control

SLC – Speed Limit Control

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More than **13%** ***Energy savings***

$\sim 0.2 \frac{kWh}{km}$ consumption reduction $\rightarrow 0.15 \frac{NIS}{km}$ savings

X

In Israel: $300{,}000{,}000\ km\ urban\ service\ per\ year^{*}$

=

$\sim 50{,}000{,}000 \left[\frac{NIS}{year}\right]$ ***Potential Savings***

*chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.gov.il/BlobFolder/reports/special_reports/he/%D7%A8%D7%99%D7%9B%D7%95%D7%96%20%D7%A0%D7%AA%D7%95%D7%A0%D7%99%D7%9D%20%D7%9E%D7%A8%D7%9B%D7%96%D7%99%D7%99%D7%9D%20%D7%91%D7%AA%D7%97%D7%91%D7%95%D7%A8%D7%94%20%D7%94%D7%A6%D7%99%D7%91%D7%95%D7%A8%D7%99%D7%AA-%20%D7%99%D7%95%D7%9C%D7%99%202021.pdf

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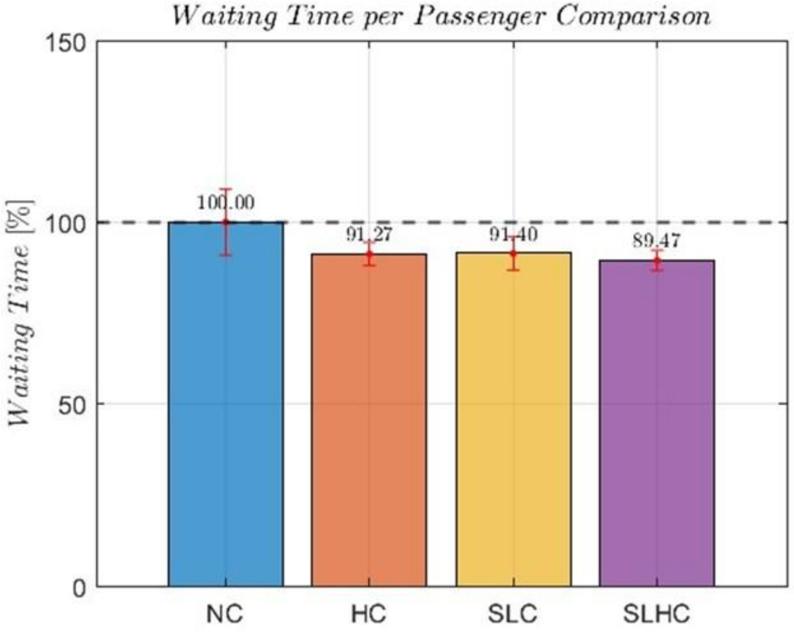
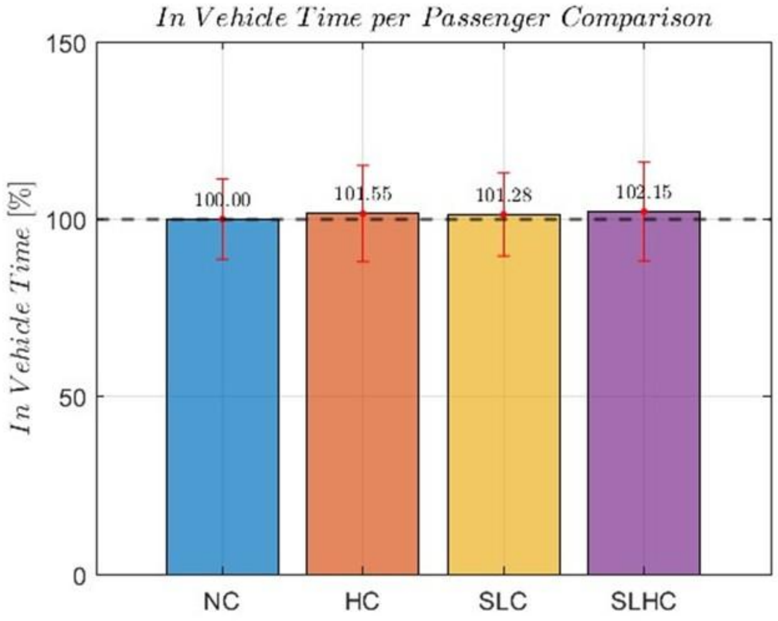
Results

- NC – No Control
- HC – Holding Control
- SLC – Speed Limit Control
- SLHC – Speed Limit & Holding Control





Impact on actual travel time:	~0.5-1 min. Waiting time reduction per passenger	=	~0.5-1 min. In-Vehicle Time increase per passenger
Impact on passengers' perceived travel time*:	**~1-2 min. Waiting time reduction per passenger**	>	**~0.5-1 min. In-Vehicle Time increase per passenger**

*Wardman, Mark. "Public transport values of time." *Transport policy* 11.4 (2004): 363-377.

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Conclusions

Public Transport System

- Combining speed limit and holding strategies yields the most effective headway regulation
- Total travel time remains nearly unchanged, as reduced waiting offsets increased in-vehicle time

Energy Consumption

- Speed limit control alone maximizes energy efficiency

Control System

- The framework remains robust across diverse case studies and under various disturbances and uncertainties

Future Work

Public Transport System

- Exploring traffic light priority as a control strategy
- Expanding the research to different modes – Light rails & Metro
- We aim to test the methodology on a real bus line and assess its performance

Energy Consumption

- Assessment of external factors: temperature, different terrains, and vehicle types

Control System

- Evaluation and comparison of different control horizons
- Add driver's non-compliance with control inputs

Thank You!

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