Cooperative Highway Merging for Heterogeneous Autonomous Traffic

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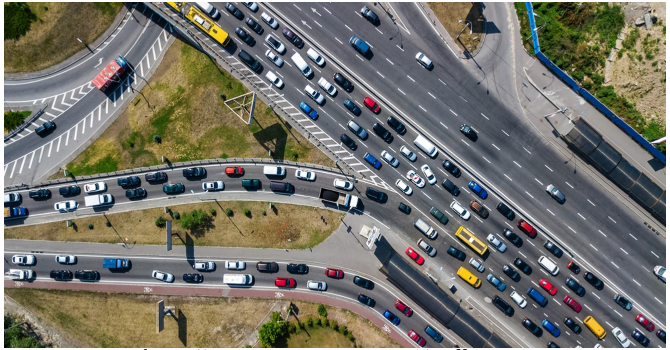
Introduction - Motivation

- The highway on-ramp merging bottleneck
  - Reduced Throughput (Mean Velocity)
  - Increased Delay
  - Increased Fuel Consumption
- Heterogeneous Traffic
  - Different vehicles ⟶ Diverse needs
- Connected Autonomous Vehicles (CAVs)
  - Enhanced sensing
  - Enhanced communication
    - Vehicle to Infrastructure (V2I) Communication
    - Vehicle to Vehicle (V2V) Communication



https://www.smartmotorist.com/traffic-jams

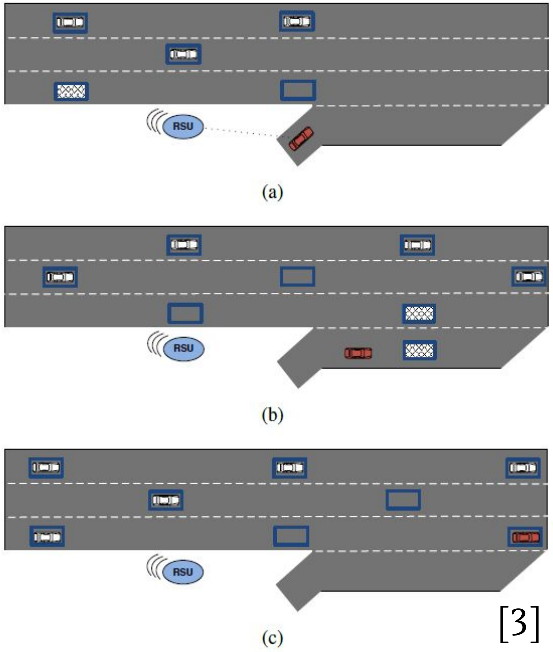
https://www.volpe.dot.gov/news/how-automated-car-platoon-works

Some Existing Methods - Literature Review

1. Optimal closed-form solution to centralized problem

2. Rule- based sequence and velocity assignment

3. Virtual slot-based allocation method

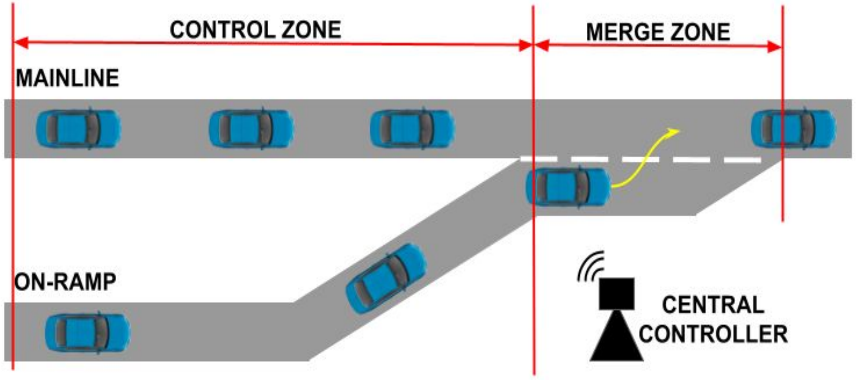


[3]

- Other methods exist to solve the optimal control problem but don't have real-time solutions
- None of these methods handle heterogeneous traffic

1. J. Rios-Torres and A. A. Malikopoulos, "Automated and cooperative vehicle merging at highway on-ramps,"IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 4, pp. 780–789, 2017.
2. J. Ding, L. Li, H. Peng, and Y. Zhang, "A rule-based cooperative merging strategy for connected and automated vehicles,"IEEE Trans. on Intelligent Transp. Systems, vol. 21, no. 8, pp. 3436–3446, 2020.
3. D. Marinescu, J.˘Curn, M. Bouroche, and V. Cahill, "On-ramp traffic merging using cooperative intelligent vehicles: A slot-based approach," in 2012 15th International IEEE Conference on Intelligent Transportation Systems, 2012, pp. 900–906

Problem Definition



Number of cars on mainline = m
Number of cars on ramp = r
Total number of cars = $n = r + m$
Speed limit = $\bar{v}$
Length of control zone = L_m and L_r
Safety Margin = $M_s = \{M_{sr}, M_{sl}\}$

Vehicle Model

- Assume existence of a low level controller for lane keeping and longitudinal actuation (w_i)

$$\dot{s}_i = f(t, s_i, w_i), \quad s_i(t_i^0) = s_i^0$$

- High level velocity control scheme

$$\dot{s}_i = v_i, \quad v_i(t) = u_i(t) \quad \text{for } i \in \{1, \ldots, n\}$$

- For each vehicle i,

$$p^i(t) \in \mathbb{R}_+^2 \qquad b^i \in \{0, 1\}$$

- Full CAV State:

$$x_i(t) = [s_i(t), v_i(t), p^i(t), b^i, l^i, a_{max}^i, a_{min}^i]^T$$

Output: Compute optimal velocities u_i and merging sequence q

Handling heterogeneous traffic

- Priority assignment based on:
  - Vehicle type, size and mass
  - Emergency vehicle
  - On-ramp or Mainline vehicle
  - Current speed
  - Vehicle’s future intent
  - Waiting time

- Types of priority:
  - Speed Prioritization p_s^i
  - Speed Variation Prioritization p_v^i

- Note: Consider flow over effect for high priority vehicles in the back of the queue

https://www.flickr.com/photos/wayy/2614120963/in/photostream/

Optimal merging control formulation

- Maximize throughput (Mean Velocity) while minimizing control (u_i) applied

$$\min_{\{u_i,q\}} \sum_{i=1}^{n} p_s^i \lambda (u_i - \bar{v})^2 + p_v^i (1-\lambda)(u_i - v_i)^2$$
$$s.t. \quad C(\{x_i\}, \bar{v}, L_m, L_r, M_s)$$

- However, this optimization problem is practically intractable
  - Constraint set C contains constraints with respect to the order of the vehicles
  - The solution to this problem, also yields the optimal sequence q
  - Problem becomes too complex to be solved in real time
- What do we do?
  - Problem can be reformulated as a mixed-integer quadratic optimization problem
    - Solved by iterating over all possible merging sequences q with exhaustive search
  - This essentially decouples the problem into:
    - Generating the merging sequence
    - Computing the optimal velocity commands u_i to achieve merging sequence q

Sequence Generation

- The problem:
  - Total number of possible sequences grows exponentially with the number of vehicles in the control zone
  - For n=30 (m=15, r= 15),
    Number of sequences is : $\frac{(m+r)!}{m!r!} = 155117520$
- Number of sequences limited by:
  - Length of the control zone
  - Requirement for FIFO order on each lane

- Our approach:
  - Rule based heuristic to select sequences q that adequately represent the search space
    - The optimal sequence lies in between the extremes of,
      - Distance to merge (d_M)
      - Time to merge (t_M)
    - Inject ramp vehicles into the mainline queue while maintaining precedence order
      - Insertion based on following logic:

$$(1-\alpha) * t_M^i + \alpha * d_M^i, \quad \forall i \in \{1, \ldots, n\}$$

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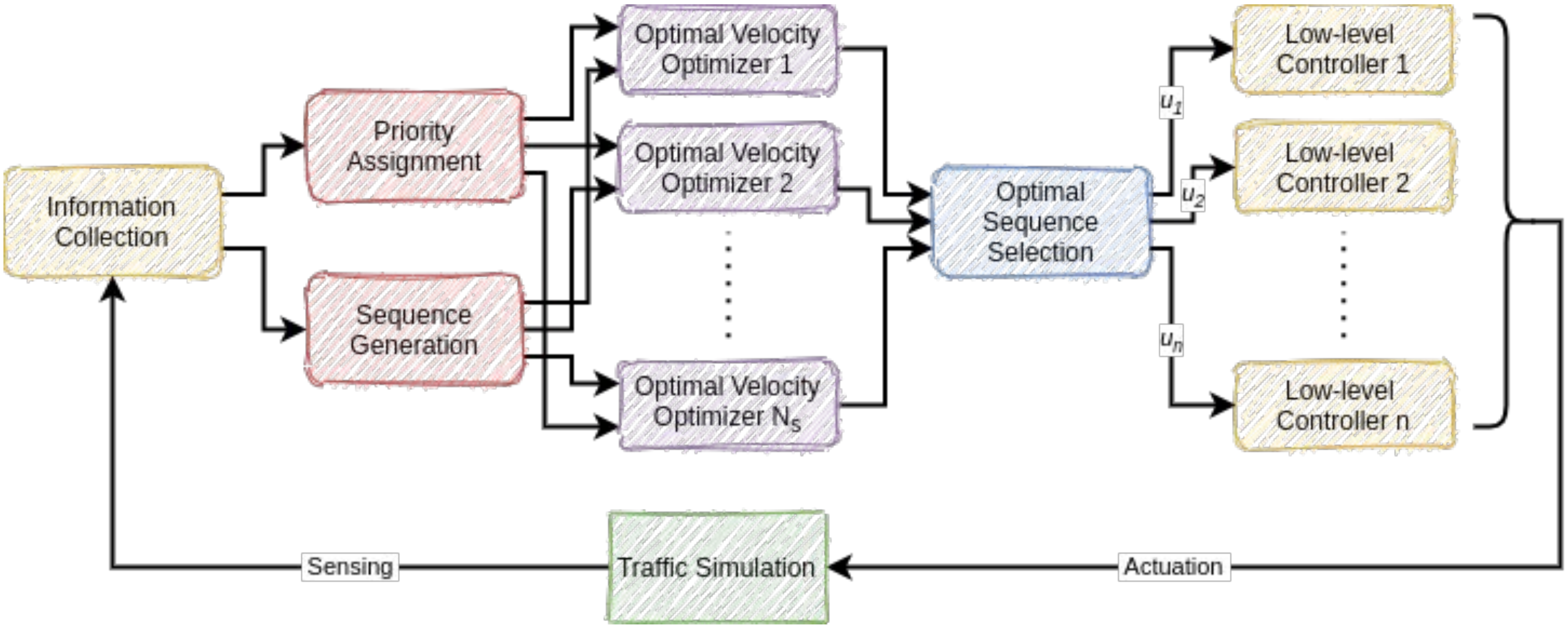
Proposed method* Pipeline



* Nilesh Suriyarachchi, Faizan M. Tariq, Christos N. Mavridis and John S. Baras, "Real-time Priority-based Cooperative Highway Merging for Heterogeneous Autonomous Traffic,"in proceedings of the Intelligent Transportation Conference(ITSC), 2021. (submitted)

Optimal Velocity Computation - Objective function

- Objective function to obtain control u_i for a given merging sequence q :

$$J(u_i|q) = \sum_{i=1}^{n} p_s^i \lambda (u_i - \bar{v})^2 + p_v^i (1-\lambda)(u_i - v_i)^2$$

- Minimize control effort and maximize throughput
  - For a fixed density (m_D),
    Throughput (m_T) is maximized when Mean velocity (m_V) is maximized

$$m_T = m_V * m_D$$

- Incorporating the variable b^i into priority p^i the problem reduced from MIQP to QP

Optimal Velocity Computation - Constraints - I

- Constraints ensure reachability and safety
- Control u_i is bounded based on :
  - Speed limits on the highway

$$0 \leq u_i(t) \leq \bar{v}$$

  - Acceleration capabilities of vehicles

$$a^i_{min} \Delta t \leq u_i(t) - v_i(t) \leq a^i_{max} \Delta t$$

    - Δt is based on the time resolution of computations

Optimal Velocity Computation - Constraints - II

- Compute expected position of vehicle i after time Δt

$$s_i(t+1) = s_i(t) - \Delta t \frac{v_i(t) + u_i(t)}{2}$$

- Rear-end collisions are then avoided by:

$$|s_j(t+1) - s_{j'}(t+1)| \geq l^j + M_{sr} \qquad \forall j, j' \in \{1, \ldots, m\}$$
$$|s_k(t+1) - s_{k'}(t+1)| \geq l^k + M_{sr} \qquad \forall k, k' \in \{1, \ldots, r\}$$

- Substituting expected position and using FIFO precedence logic

$$u_j - u_{j+1} \geq (v_{j+1} - v_j) + \frac{2}{\Delta t}(s_j - s_{j+1} + l^j + M_{sr}) \qquad \forall j, j+1 \in \{1, \ldots, m\}$$

$$u_k - u_{k+1} \geq (v_{k+1} - v_k) + \frac{2}{\Delta t}(s_k - s_{k+1} + l^k + M_{sr}) \qquad \forall k, k+1 \in \{1, \ldots, r\}$$

Optimal Velocity Computation - Constraints - III

- Compute time to merge t_m^i of vehicle i

$$t_m^i = \frac{s_i(t+1)}{u_i}$$

- Lateral collisions in merge zone are then avoided by,

$$t_m^i \leq t_m^{i+1} - \frac{l^i}{u_i} - \frac{l^{i+1}}{u_{i+1}} - M_{sl} \qquad \forall i, i+1 \in q$$

- Substituting expected position and simplifying we get,

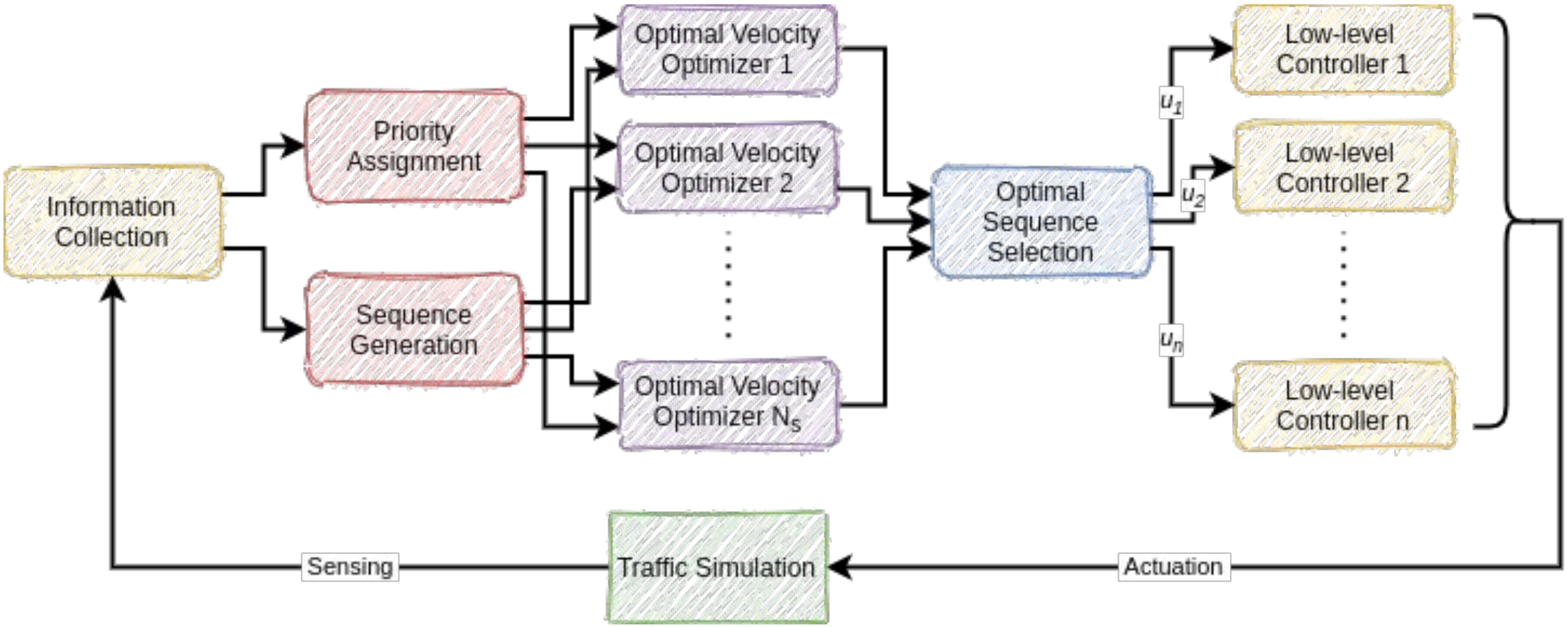
$$u_{i+1}(s_i - \frac{\Delta t}{2}.v_i + l^i + M_{sl}) \leq u_i(s_{i+1} - \frac{\Delta t}{2}.v_{i+1} - M_{sl}) \qquad \forall i, i+1 \in q$$

- This constraint also ensures merging order of sequence q is followed

Optimal Sequence Selection and Low-level Control

- Run the optimization for each sequence in parallel
- Obtain the sequence q for which the minimum objective value was achieved
- Provide the command velocities u_i corresponding to q, to the low-level controller
  - Zero communication delay is assumed for this V2I transmission
- Low-level controller executes the command
  - Compute acceleration commands to achieve desired command velocity
- Note: This method allows merging sequence to be changed at every update cycle
  - Essential feature for heterogeneous traffic
    - If an EV enters the control zone it should be given precedence

Proposed method* Pipeline



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Experimental Setup - Simulation

- Simulation Software : SUMO
- Interface platform : TraCI
- Optimization Software : Gurobi (Version 9.1.1)
- Circular loop structure used to simulate a continuous stream of vehicles with constant ratios between vehicle classes
- The percentage of mainline vehicles to ramp vehicles is easily adjusted

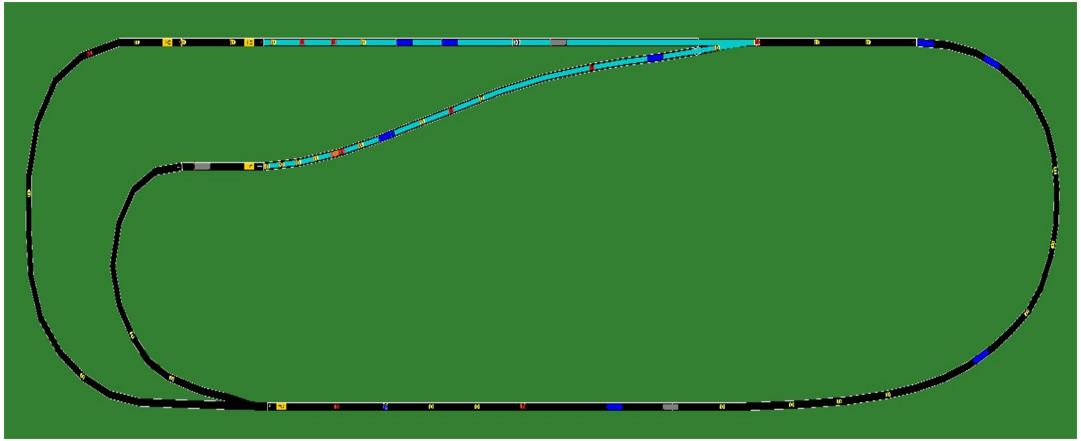
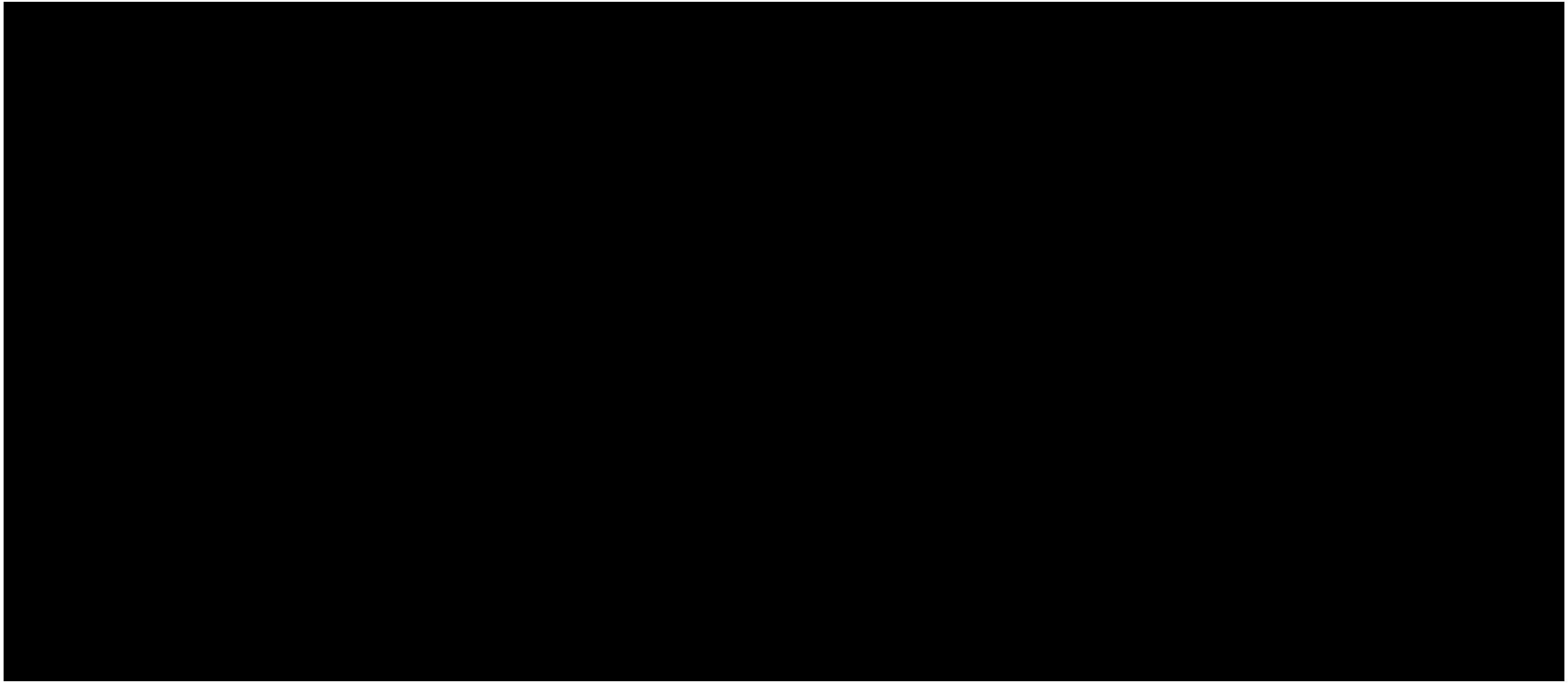


TABLE I: System parameters used in testing

Parameter	Value
Control zone length	300 m
Simulation duration	2 hrs
Time step (Δt)	100 ms
Maximum number of sequences	12
Speed limit ($\bar{v}$)	27 m/s
Mainline-Ramp rerouting ratio (r_p)	0.5
Objective trade-off (λ)	0.7
M_{sr}	2.0
M_{sl}	10.0

Proposed Method Simulation Video



Results: Methods Compared

- Compare against other real-time capable methods
  - Baseline Method
    - No cooperation between vehicles
    - Ramp vehicles give way to mainline vehicles
  - FIFO based Greedy Method
    - Vehicles assigned merging order based on entrance order to control zone
  - Zipper Merge Method
    - Merge sequence based on distance to merge
    - Alternating between ramp and mainline vehicles
  - Our Proposed Method
    - Real-time Priority-based Cooperative Highway Merging for Heterogeneous Autonomous Traffic

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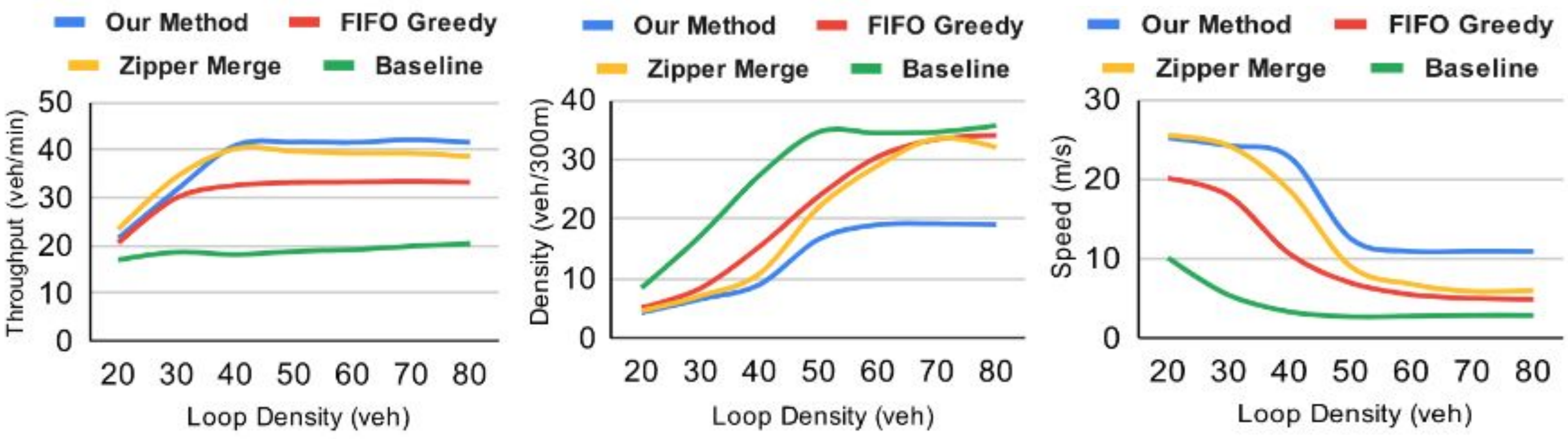
Results: Main performance indicators



(a) Throughput variation (b) Density variation (c) Mean velocity variation

- Advantages are evident at higher density levels
  - Complex methods unnecessary for low density levels
- Mean velocity improvements at high densities
  - 282% improvement over baseline
  - 81% improvement over zipper merge

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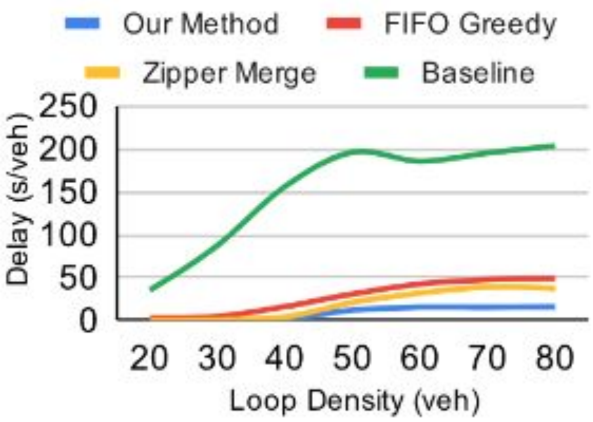
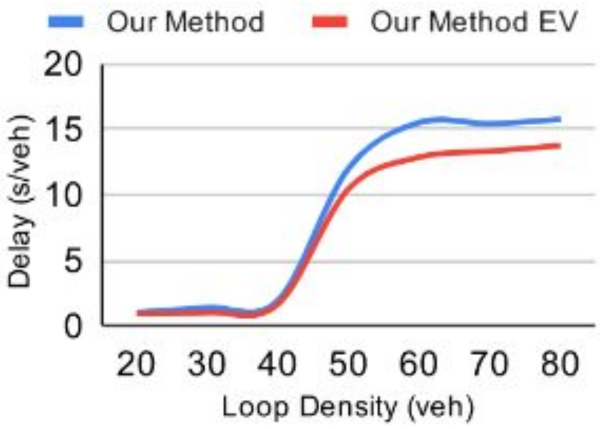
Results: Delay faced



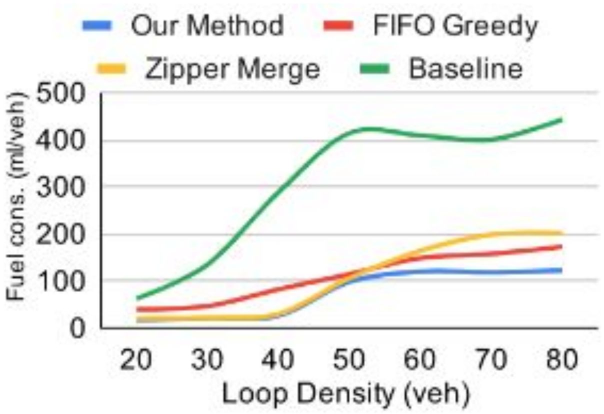
(a) Delay variation



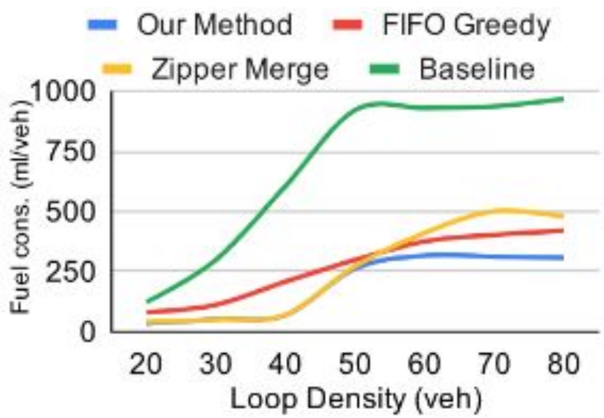
(b) EV Delay variation

- Once again, advantage of the proposed method is evident at higher density levels
  - Cooperative methods perform drastically better
- EVs face 17% less delay than other vehicle classes
- Improvements in delay faced
  - 92% improvement over baseline
  - 58% improvement over zipper merge

Results: Fuel consumption



(a) Fuel consumption variation



(b) Truck Fuel cons. variation

- Once again, advantage of the proposed method is evident at higher density levels
  - Cooperative methods perform drastically better
- Fuel savings in our method can be further improved with parameter tuning
  - Often at the cost of reduced overall throughput
- Fuel savings for trucks play an important role

Real Time Capability

- Algorithm update frequency: 10Hz (update every 100ms)

- Average time to optimize for one sequence : 25ms
  - Therefore for 12 sequences : 300ms
  - However due to parallelization : 50ms (12 core CPU)

- Algorithm is more than capable of real-time operation

- Note: The quality of the generated control can be improved even further
  - Searching over a larger number of sequences
  - Requires more computation power to maintain real-time operability

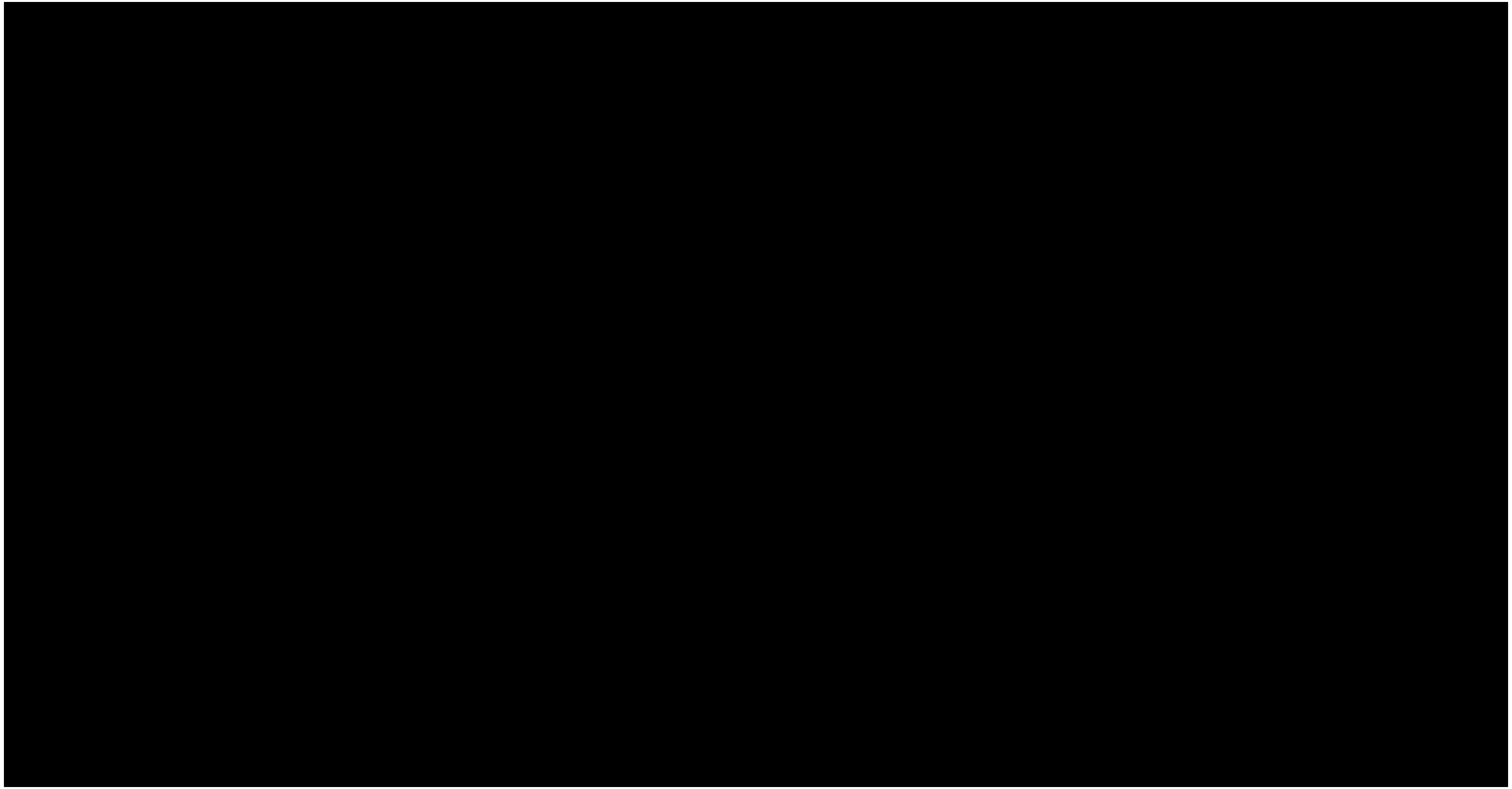
Summary

- Introduce a novel Cooperative Highway Merging method
  - Heterogeneous Autonomous Traffic (Priority-based)
  - Parallel Computation Architecture (Real-time Operation)
  - Constrained QP optimization problem

- Performance verified through SUMO simulation
  - Comparison to other real-time capable methods
  - Improvements in throughput, delay faced and fuel consumption

- What's next?
  - Multi-lane total highway capacity utilization extension
  - Decentralized control with a V2V Communication based formulation
  - RL based approach for the control aspect of this work

Sneak Peek?



Thank You!

Questions?

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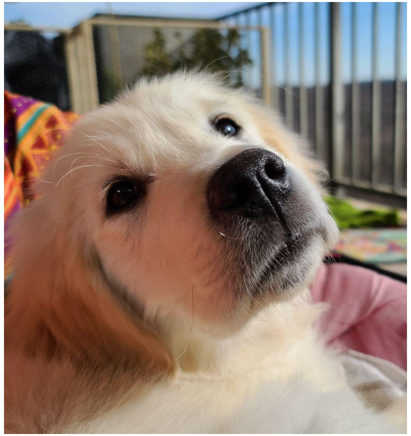

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