Optimizing Freeway Merge Operations under Conventional and Automated Vehicle Traffic

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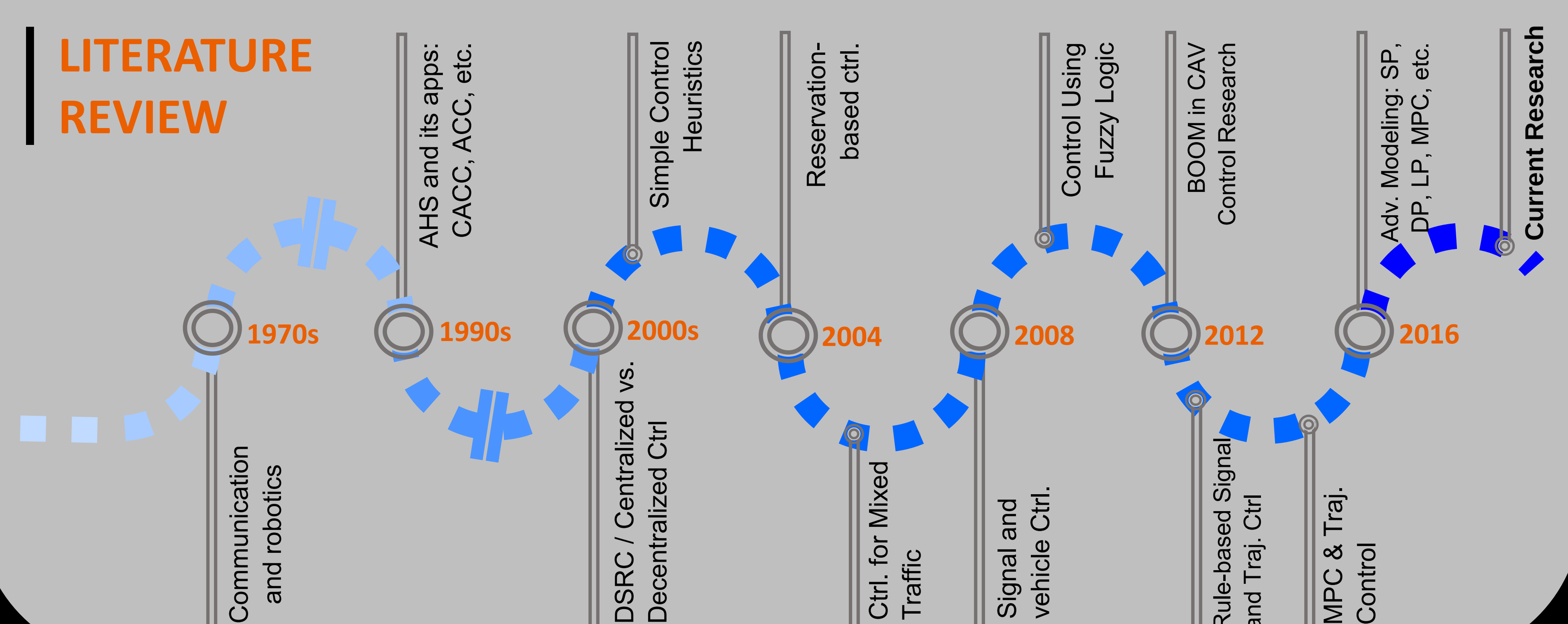
RESEARCH PURPOSE

To develop and test a centralized intelligent freeway merging control algorithm: Smart Merging System (SMS) to optimize Connected and Automated Vehicle (CV/AV) trajectories in the presence of conventional vehicles.

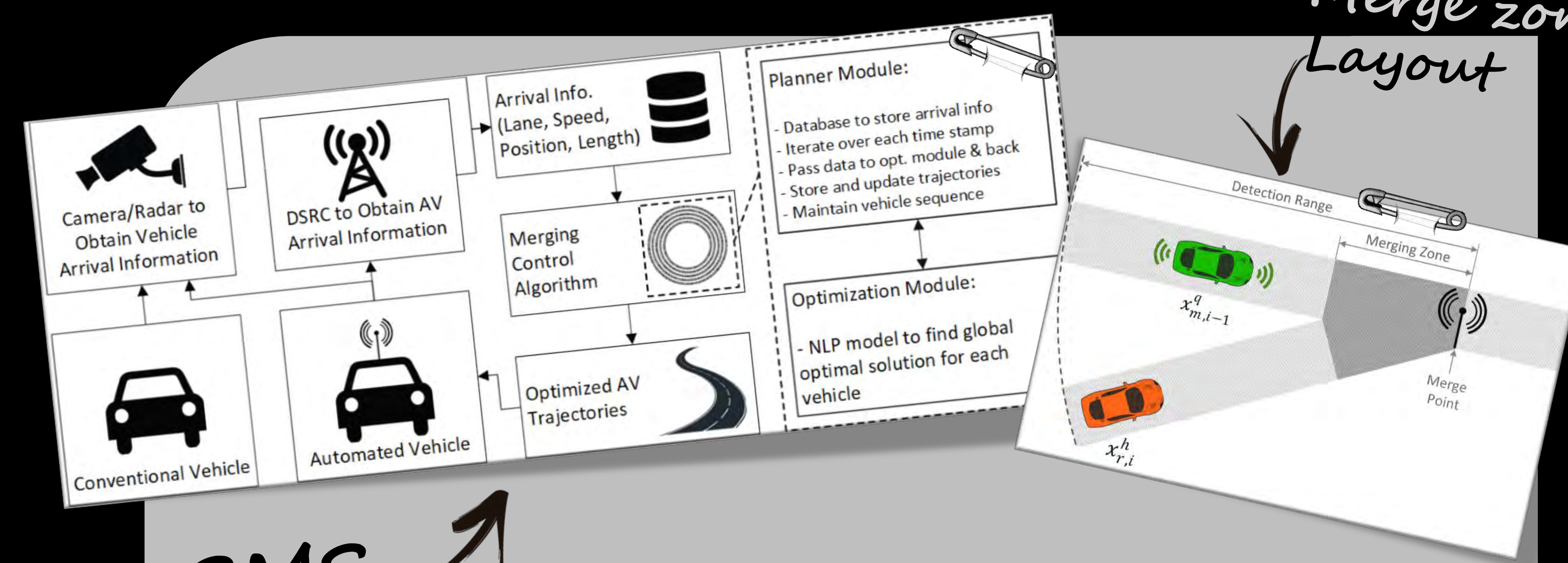
Proposed: A novel real-time nonlinear optimization model to:

- generate trajectories for AVs with the objective of maximizing the average speed of the vehicles in the system for a 2-lane segment (one lane on the freeway and one lane on the ramp).
- predict the behavior of conventional vehicles and incorporate in the trajectories of AVs.
- integrate a feedback loop system to keep track of the variation in the traffic.

LITERATURE REVIEW



SYSTEM FRAMEWORK



Planner Module runs the following steps in real-time manner (10Hz):

→ Input data source I: Arrival information through radar and cameras for both conventional vehicles and AV/CVs as they enter the comm. range (typically 1500 ft.)
→ Input data source II: AV and CV position and other pertinent information through Dedicated Short-range Communication (DSRC)

❖ Fused data entered into the algorithm → Processing and Optimization

← Output I: Optimized trajectories sent to AVs
← Output II: Speed Recommendation and guidance sent to CVs
← Output III: Prediction of conventional vehicles' behavior

Objective Function

Minimization of travel time delay and Maximization of throughput

NLP MODEL

State equations for each vehicle:

$$\dot{x}_{j,i} = f(x_{j,i}, t, a_{j,i}) \quad (1)$$

Objective Function:

$$\max_{a} \bar{v}^q_{j,i} \quad (2)$$

s.t.

$$\dot{x}^q_{j,i} = v^q_{j,i} \quad (3)$$
$$\dot{v}^q_{j,i} = a^q_{j,i} \quad (4)$$
$$a_{min} \le a^q_{j,i} \le a_{max} \quad (5)$$
$$0 \le v_j^{min} \le v^q_{j,i} \le v_j^{max} \quad (6)$$
$$x^q_{j,i} \ge x^k_{l,i-1} + G^q_u \quad (7)$$
$$x^q_{j,i} \ge x^k_{l,i-1} + G^q_w \quad \forall j \ne l \quad (8)$$
$$x^q_{j,i} \le x^{max} \quad (9)$$

PARAMETERS & VARIABLES

- $j \& l \in J = \{m, r\}$ — Indexes the road; m: Mainline, r: On-ramp
- $i = 1, 2, \dots, n$ — Indexes the vehicle
- $k \in K = \{q, h\}$ — q : If vehicle is instrumented; h : If vehicle is human − operated
- $o \in O = \{u, w\}$ — u : A pair of vehicle on the same line; w : A pair of vehicle on different lines
- $x^k_{j,i}, v^k_{j,i}, a^k_{j,i}$ — Position, velocity & input control (accel.)
- G^k_o — State – dependent minimum following distance/merging gap

Index i is the ID number assigned to each vehicle on lane j upon arrival in ascending order corresponding to the arrival time

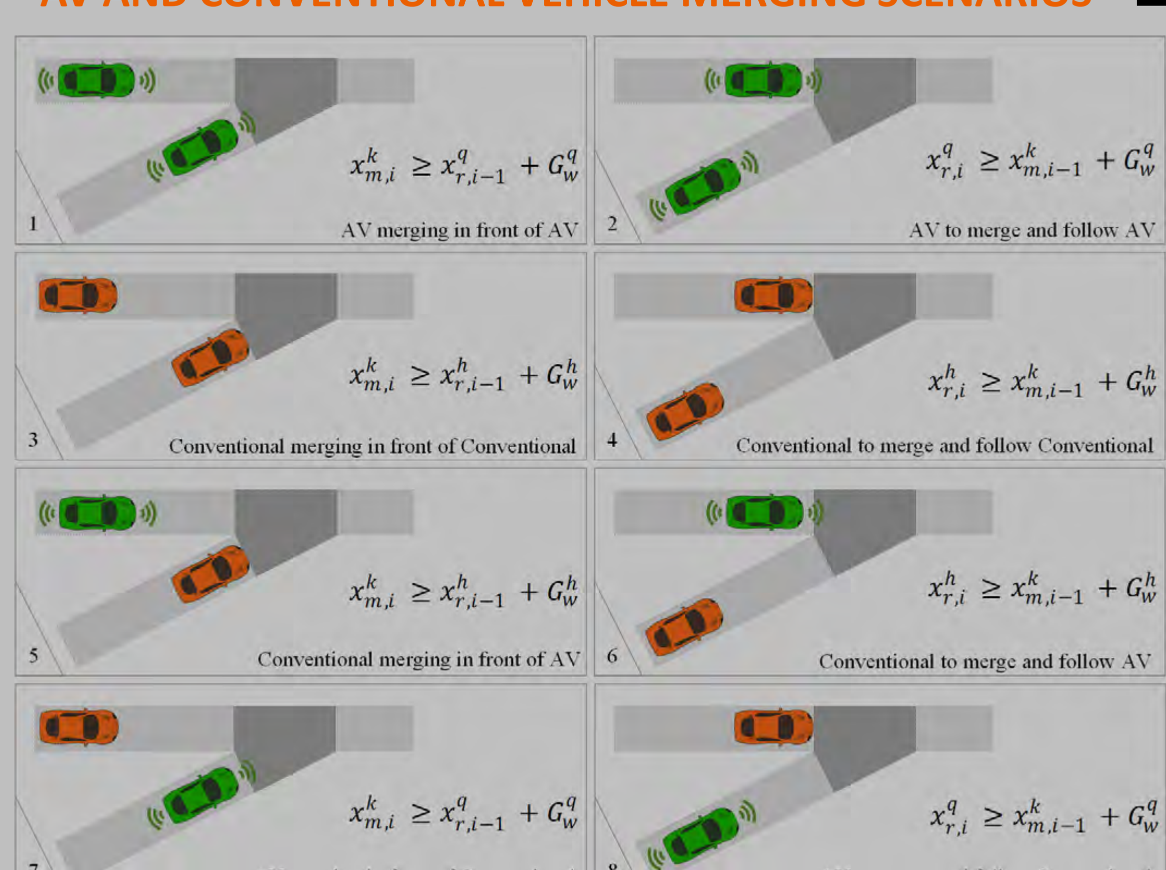
MERGING OPTIMIZATION MODULE

State and control input in (1) are defined as distance to merge point $x_{j,i}(t)$, instantaneous speed $v_{j,i}(t)$, and acceleration rate $a_{j,i}(t)$, respectively. Through Gipps car following model and (10-11) state for conventional vehicle is predicted every second. If there is a difference between detected/tracked state and predicted trajectory, feedback loop re-optimizes the merging scheme. Constraints (7-8, 10-11) are the special cases of global constraints (12-13). Where s and c be vehicle types $(c \ne s)$. Also, i and b are associated with vehicles $(i > b)$. Assuming $G^h_w \ge G^q_w \ge G^h_u \ge G^q_u$, possible scenarios are shown next.

FEEDBACK LOOP

$$x^h_{j,i} \ge x^k_{l,i-1} + G^h_u \quad (10)$$
$$x^h_{j,i} \ge x^k_{l,i-1} + G^h_w \quad \forall j \ne l \quad (11)$$
$$x^s_{j,i} \ge x^c_{j,i-1} + G^s_u \quad (12)$$
$$x^c_{j,i} \ge x^s_{l,b} + G^s_w \quad \forall j \ne l,\ i > b \quad (13)$$

AV AND CONVENTIONAL VEHICLE MERGING SCENARIOS



SIMULATION SETUP

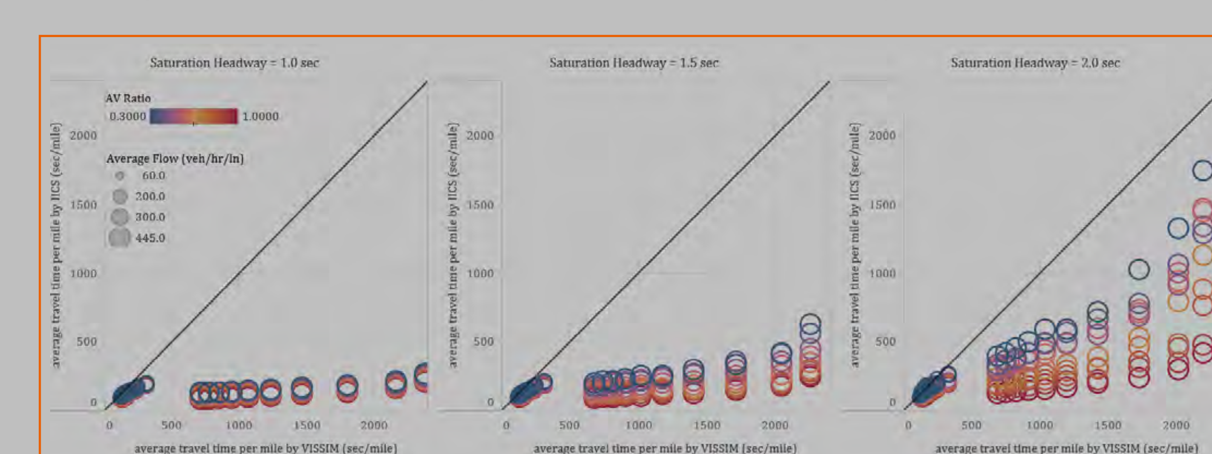
- Detection range: 153 m (500 ft.)
- Posted Speed Limit: 105 kph (65 mph)
- Demand levels (aggregated): 1000, 1400, 1800, 2200 veh/h
- Demand Split: 50-50, 65-35, 80-20 (Main-Ramp split %)
- Vehicle types: Passenger cars (1: AV & 2: Conventional)

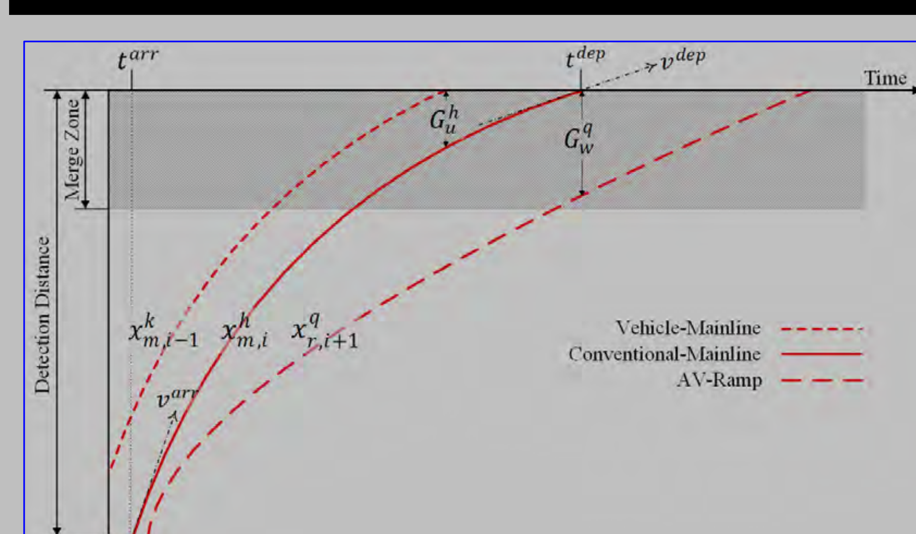
RESULTS & DISCUSSION

- An increase in AV penetration rate results in a decrease in average travel time and increase in average speed:

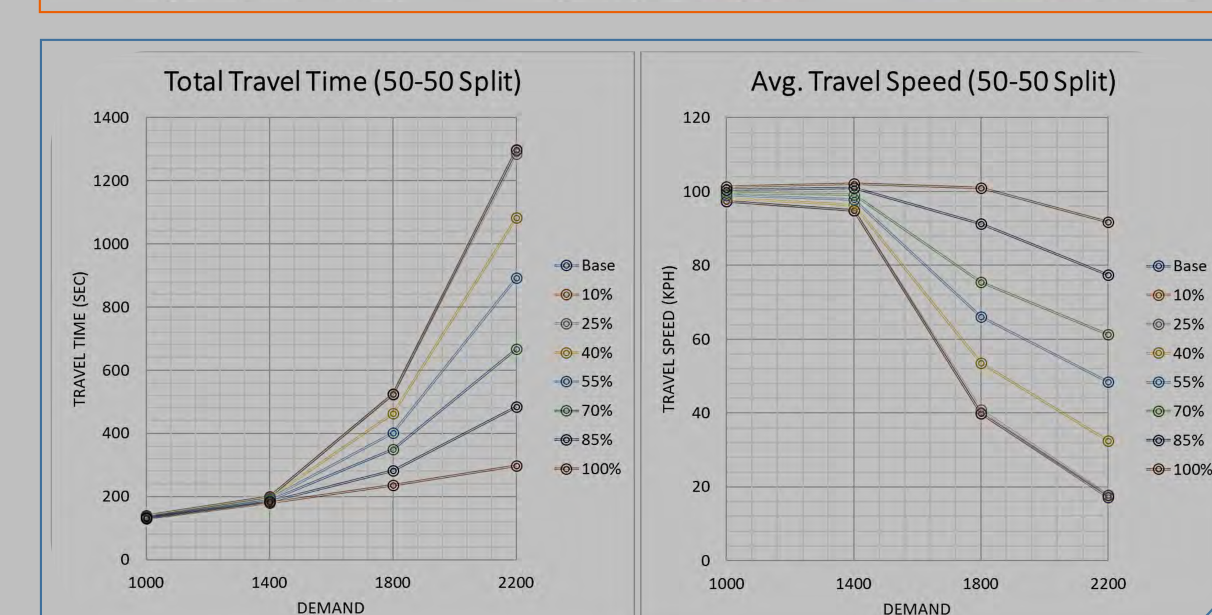
AV ratio 10%: There is minimal improvement to the system
AV ratio 25%: Minor improvements (turning point / depends on demand)
AV ratio 40%: Little improvement for low demand. High demand: up to 16.7% reduction in travel time and 18 kph increase in average speed.
Full AV: (100% Penetration rate)
Low demand: Reduction in travel time up to 6.3% for 50-50 demand split, 5.2% for 65-35 split and, 4.3% for 80-20 split
High demand: Reduction in travel time 76 - 77% for all splits

- On average for most AV ratios, 50-50 demand split has slightly better outcomes in terms of travel time and speed
  Intuition: (1) Large demand on mainline = less on-ramp vehicles to disrupt the mainline traffic = on-ramp vehicles have shorter gaps to merge in. (2) FIFO splits platoons and also drops the platoon speed if merging vehicle is the lead → 50-50 seems to be a trade-off.
- Algorithm outperformed the results from microsimulation.





An example of generated trajectories



CONCLUSIONS

- A fully AV system results in (1) shorter average travel time and (2) increased average speed by maintaining shorter gaps, better traffic operation due to shorter reaction time, and their communication capabilities.
- A minimum of 25% AV penetration rate seems to be necessary to see improvements in traffic.
- By maintaining short gaps, AVs leave a larger gap behind themselves, which helps conventional cars to use the space for merging and car following.
- The proposed algorithm showed capability in handling freeway merge operations in mixed-traffic condition effectively and efficiently.
- In practice, achieving a 70% and over AV penetration rate in the near future seems infeasible. Therefore, as a feasible and cost-effective alternative: Connected Vehicles to receive speed advisory.

LIMITATIONS AND FUTURE TRACKS

1. We assumed all drivers are average drivers in terms of behavior. It would be of merit to incorporate varying driver behaviors.
2. We focused on the processes inside the merge zone and did not study the conditions upstream and downstream of the detection zone. A future track of research could analyze system-wide operations.
3. We considered a FIFO serving order. Another future track is the study of alternative sequencing
4. We assumed no information relayed to the conventional vehicles. Researchers can study merge for mixed traffic in the presence of equipment, such as variable speed limits, ramp-metering, etc.

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ACKNOWLEDGMENT

This research is supported by National Science Foundation under grant award 1446813. This research is also funded by FDOT under Contract BDV31-977-45.

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