Multi-vehicle trajectories design during Cooperative Adaptive Cruise Control(CACC) platoon formation

by Qinzheng Wang[1], Xianfeng Yang[1], Zhitong Huang[2], Yun Yuan[1]

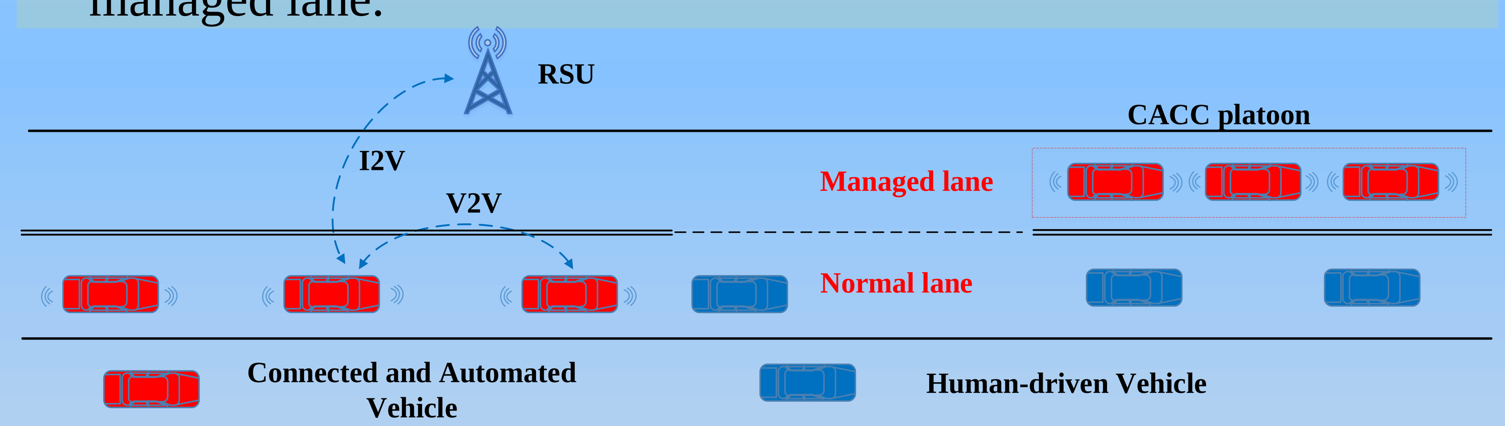
1:University of Utah;2: Leidos Inc., Saxton Transportation Operations Laboratory

Abstract

- This study aims to design optimal vehicle trajectories of CAVs during CACC platoon formation.
- A basic scenario and a destination-based protocol to determine vehicle sequence in the platoon is described.
- A space-time lattice based model is formulated to construct vehicle trajectories considering boundary conditions of kinematic limits, car-following safety, and lane changing rules. The objective is to optimize the vehicle sequence and fuel consumption simultaneously.
- A two-phase algorithm is proposed to solve this model, where the first phase is a heuristic algorithm that determines vehicle sequence and dynamic programming is adapted in the second phase to optimize fuel consumption based on the determined sequence.

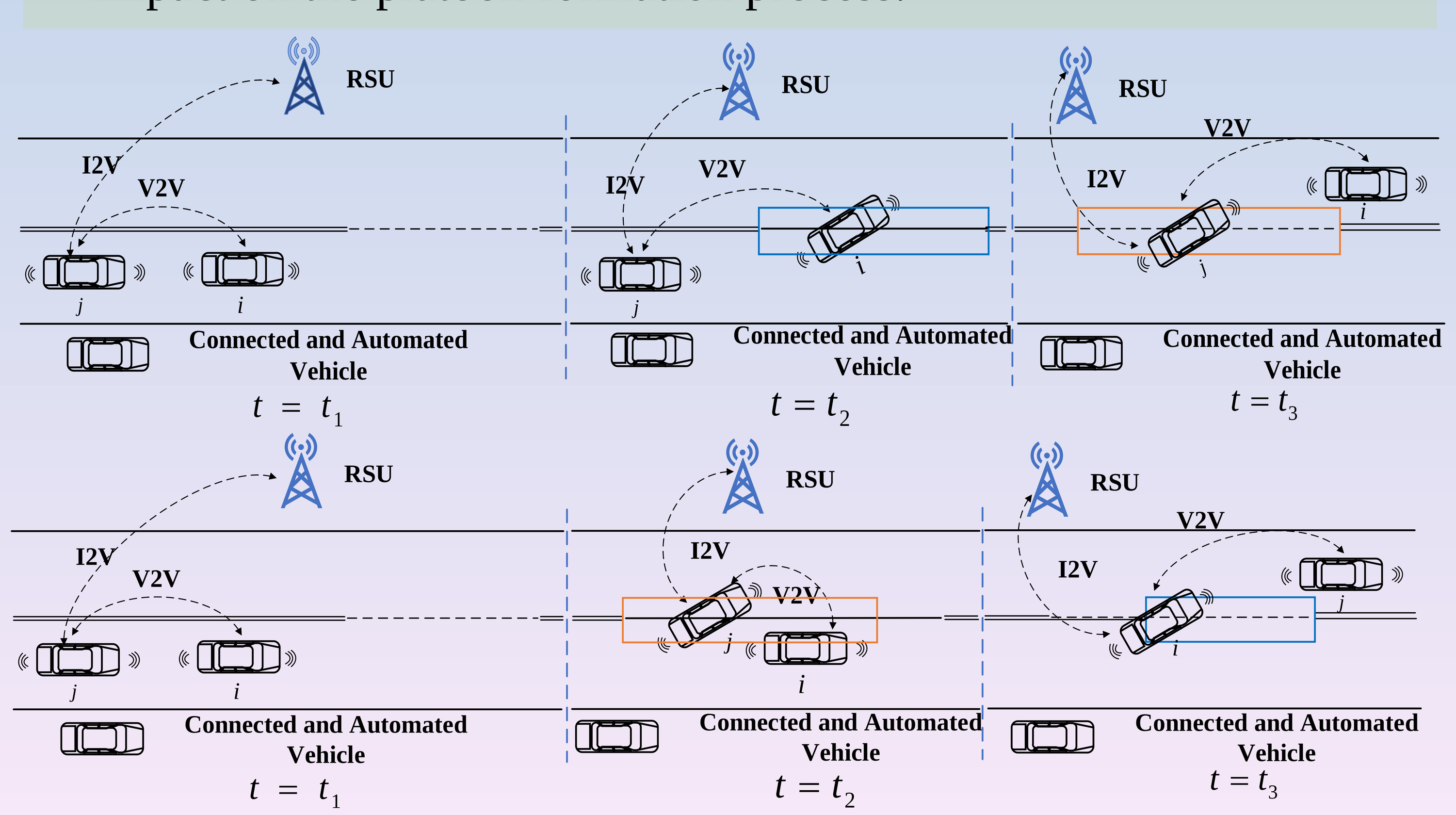
Problem Statement

- Two lanes of a freeway segment, where one is the managed lane for CAVs only and another is a normal lane opened to both CAVs and HVs. All CAVs on normal lane are ready to form a platoon on managed lane.



The basic scenario of CACC platoon formation

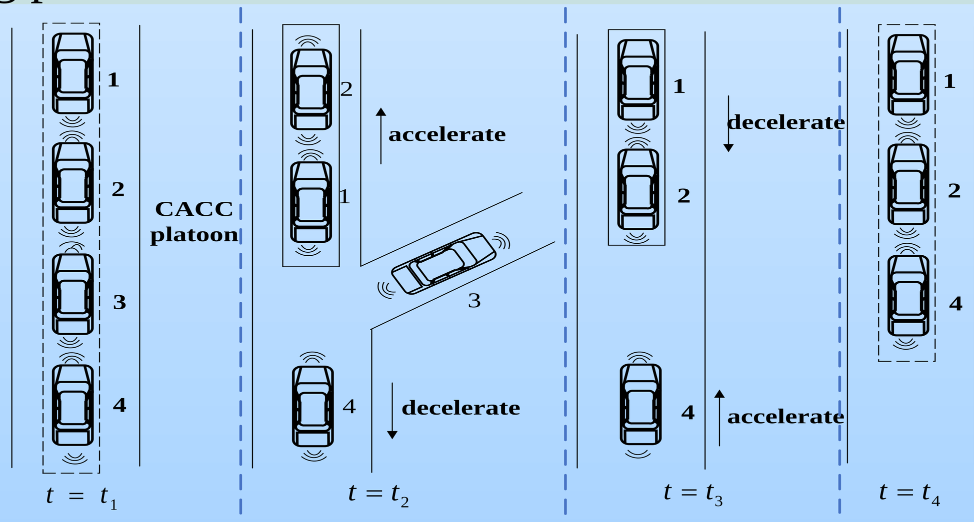
- The vehicle sequence in the CACC platoon has a significant impact on the platoon formation process.



Platoon formation process with different CACC vehicle sequence

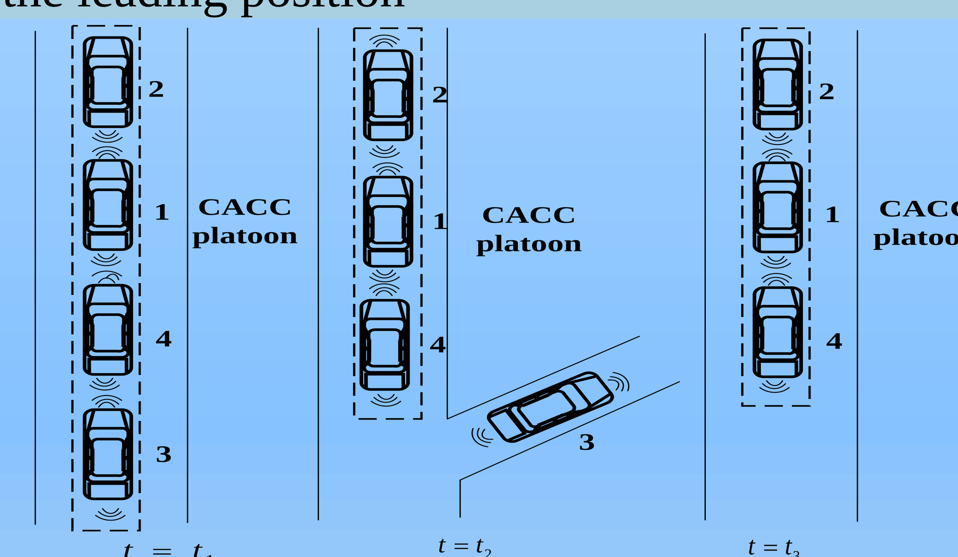
Sequence Protocol

Arrival time: the sooner a CAV arrives, the closer it is to the leading position



Process of vehicles leave the CACC platoon in which the vehicle sequence determined by arrival time

Destination: the farther the CAV's destination is, the closer it is to the leading position



Process of vehicles leave the CACC platoon in which the vehicle sequence determined by destination

Model development

$$\min(w_1 * F_1 + w_2 * F_2)$$

$$F_1 = \sum_{i=1}^{n}\sum_{j=i+1}^{n}(x_{i,K} - x_{j,K}) * f(d_{ij}, x_{ij,K}) \quad \text{sequence penalty}$$

$$F_2 = \begin{cases} \exp\left(\sum_{k=0}^{K}\sum_{i=1}^{n}\sum_{m=1}^{3}\sum_{n=1}^{3}\left(L_{m,n} * (v_{i,k})^m * (a_{i,k})^n\right)\right) & a_{i,k} \geq 0 \\ \exp\left(\sum_{k=0}^{K}\sum_{i=1}^{n}\sum_{m=1}^{3}\sum_{n=1}^{3}\left(K_{m,n} * (v_{i,k})^m * (a_{i,k})^n\right)\right) & a_{i,k} < 0 \end{cases} \quad \text{Fuel consumption}$$

s.t.

longitudinal movement:

$$v_i(k+1) = v_i(k) + a_i(k) \cdot \Delta t \qquad i \in I$$

$$x_i(k+1) = x_i(k) + v_i(k) * \Delta t + \frac{1}{2} * u_i(k) * (\Delta t)^2$$

control constraints:

$$u_i(k) \in U \qquad \forall k \in \tau;\ i \in N$$

$$v_{min} \leq v_i(k) \leq v_{max} \qquad \forall k \in \tau;\ i \in N$$

safe driving:

$$(3 - l_j^i(k) - l_j^{i'}(k) - O_{i,i'}(k)) \times M + x_i(k) - x_{i'}(k) \geq x_{safe} \ \forall\, i \in I; j \in L; k \in \tau$$

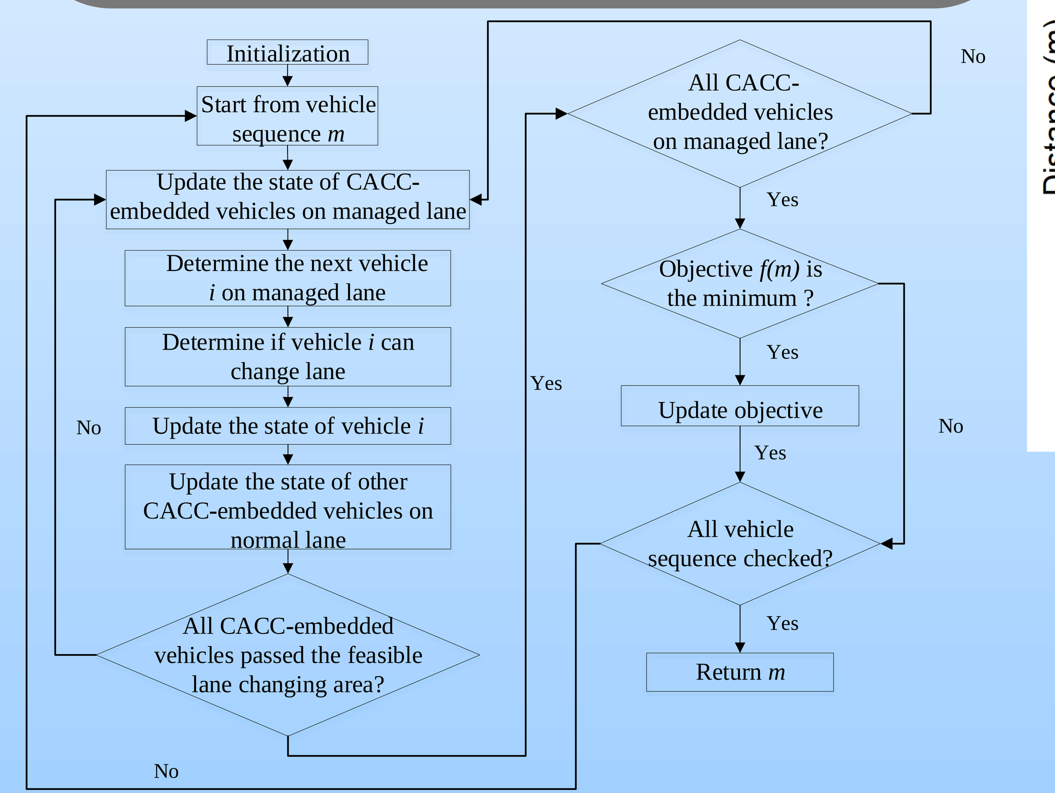
$$(2 - l_j^i(k) - l_j^{i'}(k) - O_{i,i'}(k)) \times M + x_{i'}(k) - x_i(k) \geq x_{safe} \ \forall\, i \in I; j \in L; k \in \tau$$

lane management:

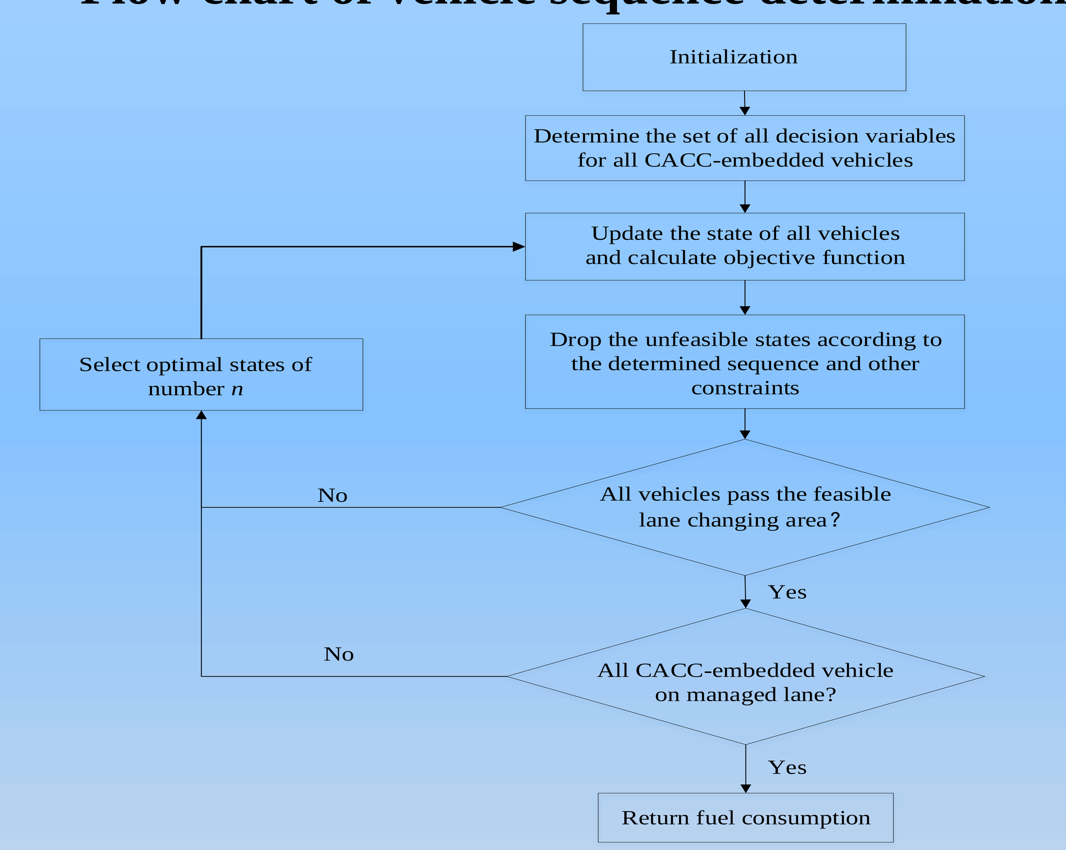
$$\sum_j l_j^i(k) = 1 \qquad \forall\, i \in I; j \in L; k \in \tau$$

$$x_s \leq \sum_0^{K_i} x_i(k) * y_i(k) \leq x_f \qquad \forall\, i \in I; k \in \tau$$

Algorithm



Flow chart of vehicle sequence determination

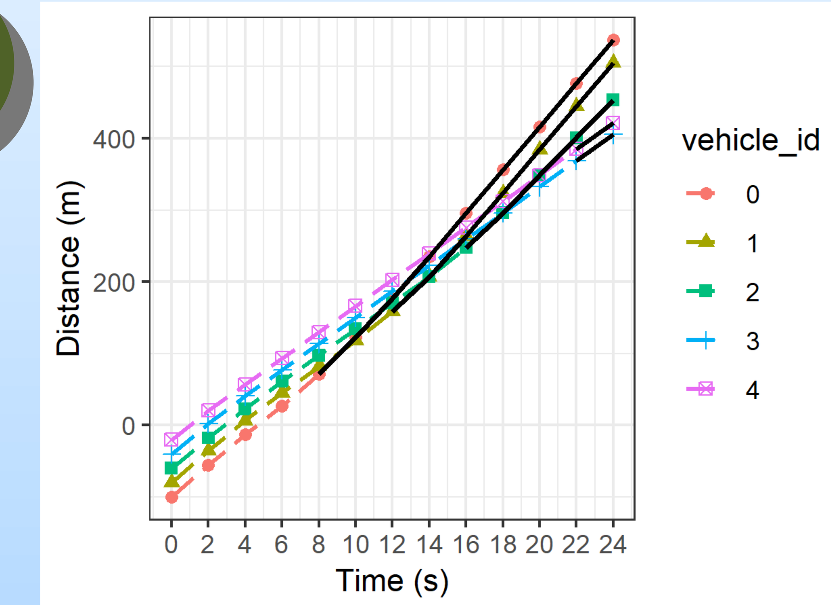


Flow chart of fuel consumption optimization

Numerical Study

Scenario descriptions:

- Five CAVs on normal lane and their locations are $x_0(0) = 20m, x_1(0) = 40m, x_2(0) = 60m, x_3(0) = 80m, x_4(0) = 100m$; their destinations are $d_0 = 6000m, d_1 = 5000m, d_2 = 4000m, d_3 = 2000m, d_4 = 3000m$
- The initial speed of those five CAVs are 80 km/h and the safe distance are 15m.
- The starting point and the length of the lane changing area are $x_s = 120m$ and 400m ;
- The control variable is from $\text{U} = \{-2\,m/s^2, -1\,m/s^2, 0\,m/s^2, 1\,m/s^2, 2\,m/s^2, \}$
- The maximum speed is 120km/h and the minimum speed is 60km/h



CAVs' trajectories during platoon formation

The total fuel consumption for all CAVs is 0.38L when the trajectories is designed without optimizing fuel consumption. After optimization, the total fuel consumption has been reduced to 0.21L, which is about 45% of reduction.

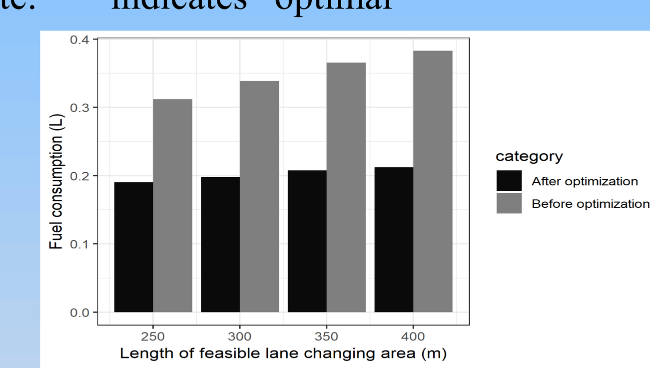
CAVs' sequence in CACC platoon with various situations

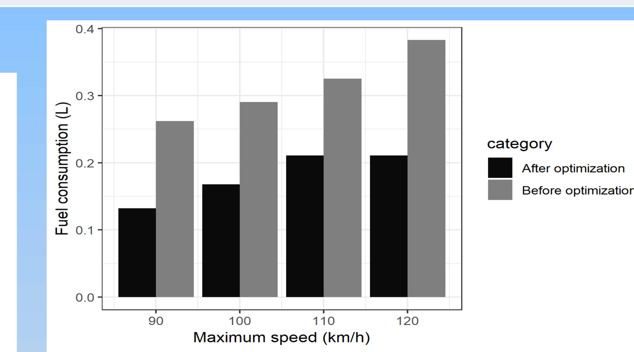
Length of feasible lane-changing area (m)	Final vehicle sequence
250	vehicle2 - vehicle0 -vehicle4 - vehicle3 - vehicle1
300	vehicle1 - vehicle0 -vehicle4 - vehicle3 – vehicle2
350	vehicle1 - vehicle0 -vehicle4 - vehicle3 – vehicle2
400	Vehicle0 – vehicle1 -vehicle2 – vehicle4 – vehicle3*

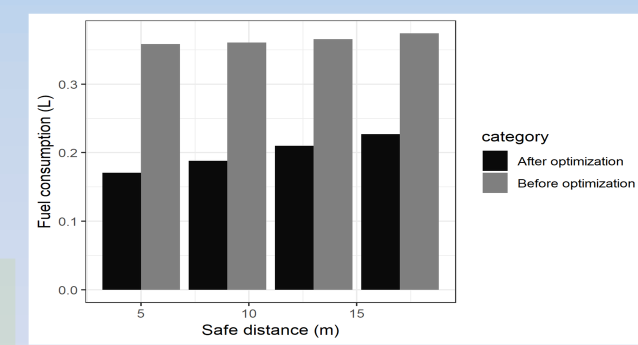
Maximum speed (km/h)	Final vehicle sequence
90	Vehicle1 - vehicle0 -vehicle2 – vehicle4 – vehicle3
100	Vehicle0 – vehicle2 -vehicle1 – vehicle4 – vehicle3
110	Vehicle0 – vehicle1 -vehicle2 – vehicle4 – vehicle3*
120	Vehicle0 – vehicle1 -vehicle2 – vehicle4 – vehicle3*

Safe gap (m)	Final vehicle sequence
5	Vehicle0 – vehicle1 -vehicle2 – vehicle4 – vehicle3*
9	Vehicle0 – vehicle1 -vehicle2 – vehicle4 – vehicle3*
13	Vehicle1 – vehicle0 -vehicle2 – vehicle4 – vehicle3
17	Vehicle1 – vehicle0 -vehicle2 – vehicle4 – vehicle3

Note: "*" indicates "optimal"







- The achievement of optimal sequence subjects to many factors.
- The fuel consumption of the optimized trajectories were reduced by 42%, 46% and 43% on average.

Conclusions

- This study proposed a model to design trajectories of CAVs during CACC platoon formation that yields optimum performance on vehicle sequence, with an objective of minimum total fuel consumption.
- Using numerical tests, the proposed model and algorithm has shown its promise in optimizing CACC vehicle sequence and fuel consumption with a promising computation efficiency.