Vehicle Autonomy in Laneless Multi-Commodity and Heterogeneous Traffic

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Connected and Autonomous Vehicles

Evolution of the automobile industry:
Purely mechanical systems → electro-mechanical systems → automotive CPS.

Resemblance of modern day vehicles†

Connected Vehicles

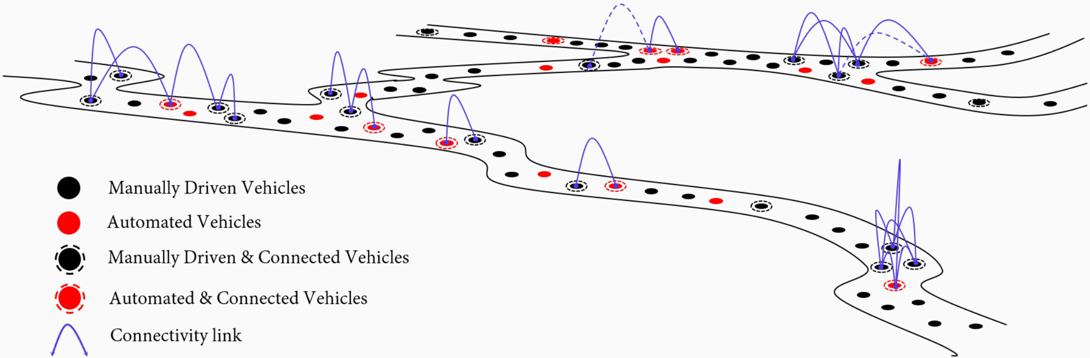
Self Driving Cars†

† www.freepick.com

Challenges and Opportunities

What makes Indian Traffic problems hard?
What are the challenges and opportunities does it present?

Multi-commodity and Heterogeneous Traffic



- **Multi-Commodity traffic** - comprising vehicles with different dynamics.
- **Heterogeneous traffic** - comprising vehicles with varying connectivity and control.
- **Laneless traffic** - traffic without dedicated and distinct lanes.

Challenges and Opportunities

Laneless Traffic

- Traffic flow models build upon concepts of 1-dimensional fluid flow.
- Properties satisfy due to presence of dedicated lanes.

Multi-Commodity Traffic

- Vehicles of different utility move on same lanes.
- Assumption of uniform vehicle dynamics no longer holds.

Heterogeneous Traffic

- Vehicles with different levels of autonomy present together in the same traffic.
- Decision making patterns vary and so do their cooperative nature.

Uncertainties

Challenges and Opportunities

‘How do we design a controller for partial or full autonomy of vehicle maneuver in laneless, multi-commodity and heterogeneous traffic?’

Challenges and Opportunities

- To develop a new framework for laneless, multi-commodity and heterogeneous (LMH) traffic.
  - To develop models for **vehicle mobility** in LHM traffic scenario.
  - **Control algorithm** for maneuver of autonomous and semi-autonomous vehicles.
- To develop a scaled down test setup for exploring the feasibility and effectiveness of connected and (semi-)autonomous vehicles in LMH traffic scenario.
  - Development of **small scale autonomous (and connected) electric vehicles**.
  - To study the effects of **connectivity** and **autonomy** in LHM traffic scenario.

Vehicle Transportation Network

The elements of a vehicle transportation network, affecting the mobility of vehicles directly or indirectly, can be classified as:

- Vehicles
- Road side units
- Connected vehicle infrastructure
- Roads

'How to deal with all the elements together?'

[1] Kumar, Subhadeep, Ramkrishna Pasumarthy, and Nirav P. Bhatt. "A Game Theoretic Formulation of Path Selection in Urban Transportation Networks." *2019 Fifth Indian Control Conference (ICC)*. IEEE, 2019.

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The vehicle transportation network can be formulated as a multilayered multiplexed network[1]

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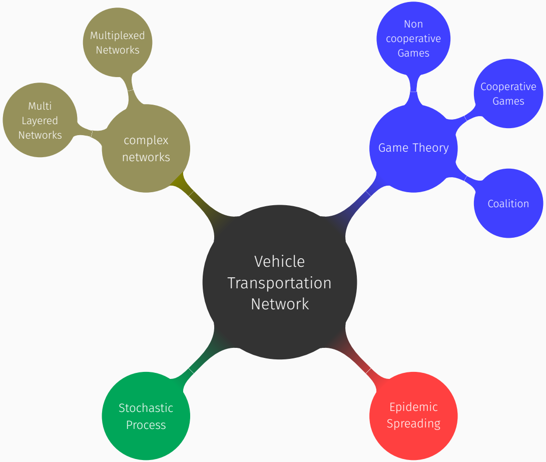
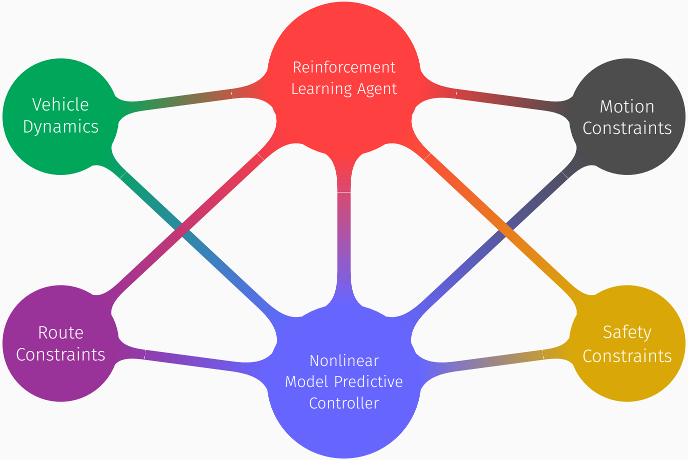
Framework



Framework for vehicle mobility

Control Strategy

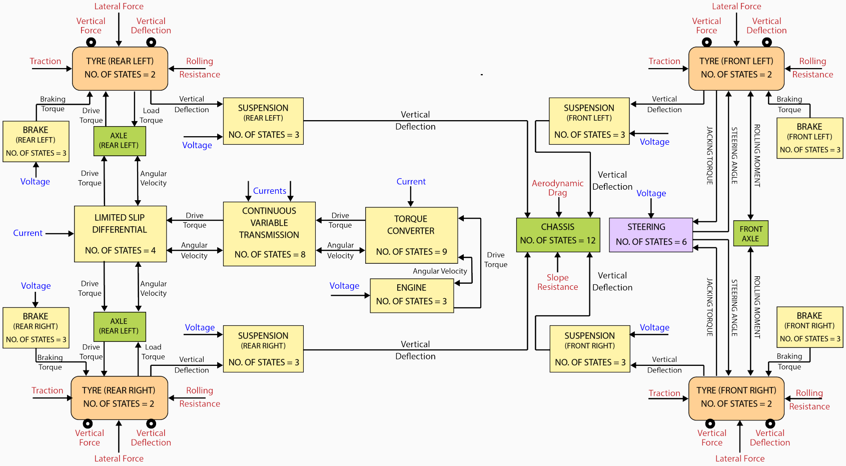


Control strategy for (semi-)autonomous vehicles

Vehicle Model

- Data for all possible scenarios is necessary for training the RL agent. *cannot be obtained by real-life testing*
- **Vehicle simulator** is one of the solution.
- Existing vehicle models and simulators captures mostly the steady state behaviour.
- Detailed model necessary to capture the transient behaviour.
- NMPC can take over the control at specific conditions and ensure safety.
- Also useful for predictive health monitoring. With a good model, state of the subsystems can be analysed in a better fashion.

Vehicle Model



Model block diagram for a combustion vehicle

The Path Selection Game

Game between nodes of the Vehicle Mobility Networks (vehicles) and the enterprises providing route assistance.

Objectives:

- **Vehicle users:** Reducing travel time, fuel consumption or comfortable trip.
- **Enterprises:** Increasing number of users.

Actions:

- **Vehicle users:** Follow path suggested by enterprise or not follow.
- **Enterprises:** Route determination for different origin-destination (OD) pairs.

Game Type:

- Combination of cooperative and non-cooperative game. Also repeated game.

Nature of Information: Incomplete

The game can be formulated as a repeated Stackelberg game

Utility of vehicle users:

Can be expressed as a function of **fuel consumption**, **travel time** and **comfort index** with time varying weights for each quantity.

$$U_i(\varkappa_i(t), t) \;=\; c_f^i(t) f_j^i(t) + c_t^i(t) T_{jf}^i(\varkappa_i) + c_c^i(t) C_j^i(\varkappa_i, t)$$

where

- c_f^i, c_t^i and c_c^i are the weights for fuel consumption, travel time and comfort of the passenger at time t.
- $C_j^i(\varkappa_i(t), t)$ is the comfort index of player v_i as a function of its location, $\varkappa_i(t)$, at time t.

The Path Selection Game

Let,

- the number of available routes to an user, present in an edge between two nodes in the road network m and n, say e_{mn}, at time t, be $s_i(e_{mn}, t)$,
- the set of all possible routes be $r_i(e_{mn}, t) = \{r^i_j(t)\}_{j=1}^{s_i}$,
- the travel time predicted by enterprise ε for the routes at time (t_{k_ε}) be $T^{i\varepsilon}_f(z^0_i) = \{T^{i\varepsilon}_{jf}\}_j^{s_{i\varepsilon}}$, where $s_{i\varepsilon}(t_{k_\varepsilon}) \leq s_i(t_{k_\varepsilon})$,
- the set of routes predicted by enterprise ε be $r_{i\varepsilon}(e_{mn}, t_{k_\varepsilon})$, and
- at time t, user in v_i use services of $b(t)$ enterprises and the probability assigned for lottery of enterprise ε be β^ε_i.

The Path Selection Game

- For an user travelling in $v_i \in \left(V(t) \times \mathbf{L}_v \times \mathbf{L}_V\right)$, the lottery of route provided by enterprise ε is given by:

$$\mathcal{L}_{i\varepsilon} = \left(p_1^{i\varepsilon} : r_1^i(t_{k_\varepsilon}),\ p_2^{i\varepsilon} : r_2^i(t_{k_\varepsilon}), \cdots,\ p_{s_{i\varepsilon}}^{i\varepsilon} : r_{s_{i\varepsilon}}^i(t_{k_\varepsilon})\right)$$

$$p_j^{i\varepsilon}\left(r_j^i(t_{k_\varepsilon})\right) = \begin{cases} \dfrac{\left(\sum_{k\neq j}(T_{kf}^{i\varepsilon})^{-1}\right)^{-1}}{T_{jf}^{i\varepsilon} + \left(\sum_{k\neq j}(T_{kf}^{i\varepsilon})^{-1}\right)^{-1}}, & \text{if } r_j^i(t_{k_\varepsilon}) \in r_i(e_{mn}, t_{k_\varepsilon}) \\ 0, & \text{otherwise} \end{cases}$$

- Then, at time t_{p_i}, where $t_{k_\varepsilon} \leq t_{p_i} \leq t_{k_\varepsilon+1}\ \forall\ \varepsilon$, the compound lottery is given by:

$$\mathcal{L}_i(t_{p_i}) = \left(\beta_i^1 : \mathcal{L}_{i1},\ \beta_i^2 : \mathcal{L}_{i2}, \cdots,\ \beta_i^{b(t_{p_i})} : \mathcal{L}_{ib(t_{p_i})}\right)$$

$$\beta_j^i = \beta\left(\mathcal{L}_{ij}(t_{p_i}) \,\middle|\, \bigcup_{\kappa=0}^{t_{p_i}} \vartheta(\kappa)\right), \sum_{j=1}^{s_i} \beta_j^i = 1$$

The Path Selection Game

- The simple lottery obtained from the compound lottery is given by:

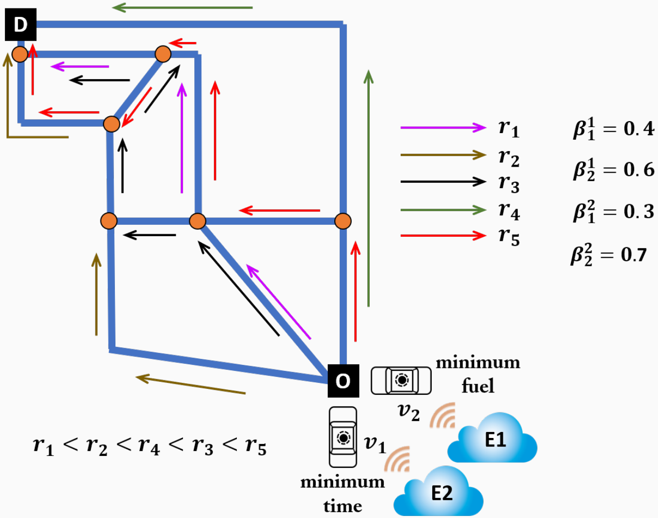
$$\left(\alpha_1^i : r_1^i(t_{p_i}), \cdots, \alpha_{s_i(t_{p_i})}^i : r_1^i(t_{p_i})\right)$$
$$\alpha_j^i = \sum_{\varepsilon} p_j^{i\varepsilon} \beta_\varepsilon^i$$

- **Choice of route** depends on the risk behaviour and utility of the user and varies from user to user.

- As users chooses their route, the enterprises provides another set of route prediction. Again the process repeats.

- In this game, **enterprises** are the leaders and **users** are the followers.

Example


D
O
r_1
r_2
r_3
r_4
r_5
$\beta_1^1 = 0.4$
$\beta_2^1 = 0.6$
$\beta_1^2 = 0.3$
$\beta_2^2 = 0.7$
minimum fuel
v_2
v_1
minimum time
E1
E2
$r_1 < r_2 < r_4 < r_3 < r_5$

Example

- Let the information sent to both vehicle from E_1 and E_2 be

$$(45\,\text{min} : r_1,\ 35\,\text{min} : r_2,\ 40\,\text{min} : r_3,\ 30\,\text{min} : r_4,\ 55\,\text{min} : r_5) \ \text{ and}$$

$$(42\,\text{min} : r_1,\ 31\,\text{min} : r_2,\ 45\,\text{min} : r_3,\ 33\,\text{min} : r_4,\ ), \quad \text{respectively}$$

- Then,

$$\mathcal{L}_1 = (0.175 : r_1,\ 0.224 : r_2,\ 0.196 : r_3,\ 0.262 : r_4,\ 0.143 : r_5),$$
$$\mathcal{L}_2 = (0.219 : r_1,\ 0.297 : r_2,\ 0.205 : r_3,\ 0.279 : r_4,\ 0 : r_5)$$

- The final lottery of route for user in v_1 is

$$(0.201 : r_1,\ 0.268 : r_2,\ 0.201 : r_3,\ 0.272 : r_4,\ 0.057 : r_5)$$

- Since, the utility of user 1 is prioritized by least travel time, he/she chooses r_4.
- The final lottery of route for user 2 is

$$(0.206 : r_1,\ 0.275 : r_2,\ 0.202 : r_3,\ 0.274 : r_4,\ 0.043 : r_5)$$

- The utility of user 2 is prioritized by least fuel consumption. So, user 2 chooses r_2 as the probability for r_2 and r_4 is almost same.

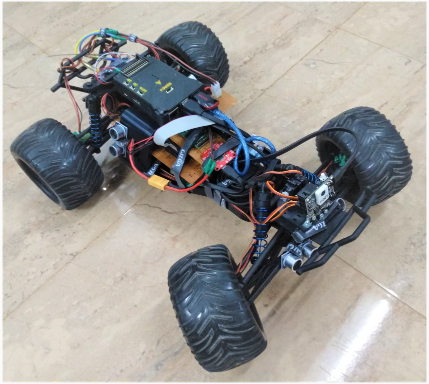
Infrastructure Developed

Cloud Infrastructure

- Eucalyptus and OpenStack cloud platform.

Electric Vehicles

- Small scale electric vehicles with few autonomous maneuvering features.



Electric Vehicle

Questions?