AVCB:
The Mobility Challenge

Yellow Paper

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- creation of optimal vehilce platooning strategies for formation of physical layer for a vehicle edge network

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6.4 Platoon Characteristic

In this section the mathematical formulation of the key characteristics and metrics involved in the platooning framework are defined. The metrics are formed in a distributed manner, meaning that in a given road network of connected communicating vehicles, every vehicle is collecting data from its surrounding environment and constructs a localized statistical model. Each vehicle measures the platoon characteristics and performs local analyitics from this model, and these results drive the behavior of each vehicles local controller model. Each of the following metrics is, therefore, formulated with respect to some given reference vehicle $v_n \in V$ for a given set of vehicle V. It is important to note that, in this work, the measurements of a vehicle's mobility characteristics (e.g. it's speed, velocity, etc...) are assume the origin of measurements are from the center of the vehicle.

**Measurements of position/velocity/etc... assume origin of measurements at center of vehicle

6.4.1 Random Variables

Due to the highly variable nature of the characteristics involved in the formation of optimal vehicle platoons, a stochastic framework was chosen as to give the most accurate mathematical model.

6.4.2 Speed

v_n

6.4.3 Gap

The gap between two vehicles is defined as the displacement between two vehicles, a lead vehicle and a follow vehicle. The mathematical formulaion is as follows:

$\Delta l_n = |l_{lead} - l_{follow}|$

6.4.4 Headway

The vehicle headway is defined as the displacement between two vehicles, a following and a lead vehicle, divided by the velocity of the following vehicle. The mathematical formulaion is as follows:

$h_n = \frac{\Delta l_n}{v_{follow}}$

6.4.5 Platoon Size

6.4.6 Platoon Density

6.4.7 Platoon Lifetime

6.4.8 Platoon Dispersion

6.4.9 Platoon Variability

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6.12 Crowding

6.12.1 Characteristics

Empirical rules:

- **Flock centering:** agents stay together with/nearby other agents
- **Collision avoidance:** avoid colliding with other agents
- **Velocity matching:** keep similar velocity with other agents

6.12.2 Type Models

6.12.3 Eulerian Models

6.12.4 Lagrangian Models

6.12.5 Balance of Forces

As the vehicles move in the environemnt, a series of "forces" acts upon them, pulling or pushing them in certain directions and controlling their overall behavior. Vehicles take into account these forces by measuring and recording information from their environment through either sensors, or via the communcation network. Upon receiving information from the environment, the vehicle reacts to the "forces" that it detects from the environment. These forces become the main focus of the controller as through their manipulation, the vehicles will be able to achieve their local objectives and the platoon will be able to achieve its globalized objectives as well.

Table 1: Platooning Forces

Force	**Notation**	**Type**	**Description**
Crowding	$F_{crowding}$	Attractive	force pulling vehicles in platoon toward one another
Foci	F_{foci}	Attractive	Forces which the vehicles desire
Vehicle	$F_{Vehicle}$	Repulsive	Forces emmitted from individual vehicles

7 Vehicle Dynamics Modeling

7.1 Overview

8 Platoon Negotiations

Dealing with misalignment of interests

8.1 Attitude

8.1.1 Cooperation

8.1.2 Non Cooperation

9 Platooning Controls Framework

9.1 Overview

9.2 Data Structures

9.3 States

Table 2: Platoon States

State	Notation	Value	Description
Formation	$s_{formation}$	0	force pulling vehicles in platoon toward one another
Dissolution	$s_{dissolution}$	1	Forces which the vehicles desire
Modification	$s_{modification}$	2	Forces which the vehicles desire
Disruption	$s_{disruption}$	3	Forces which the vehicles desire
Regroup	$s_{regroup}$	4	Forces which the vehicles desire
Negotation	$s_{negotation}$	4	Forces which the vehicles desire

9.4 Maneuvers

Table 3: Platoon Maneuvers

Maneuver	Notation	Value	Description
Join	m_{join}	0	force pulling vehicles in platoon toward one another
Leave	m_{leave}	1	Forces which the vehicles desire
Merge	m_{merge}	2	Forces which the vehicles desire
Split	m_{split}	3	Forces which the vehicles desire
Regroup	$m_{regroup}$	4	Forces which the vehicles desire

Table 4: Vehicle Maneuvers

Maneuver	**Notation**	**Value**	**Description**
Approach	$m_{Approach}$	0	force pulling vehicles in platoon toward one another
Regress	$m_{Regress}$	1	Forces which the vehicles desire
Enter	m_{enter}	2	Forces which the vehicles desire
Exit	m_{exit}	3	Forces which the vehicles desire

9.5 Publisher Subscriber Model

9.5.1 Overview

9.5.2 Model

9.5.3 Messages

Table 5: Platoon Messages

Message	**Notation**	**Value**	**Description**
Join	m_{join}	0	force pulling vehicles in platoon toward one another
Leave	m_{leave}	1	Forces which the vehicles desire
Merge	m_{merge}	2	Forces which the vehicles desire
Split	m_{split}	3	Forces which the vehicles desire
Regroup	$m_{regroup}$	4	Forces which the vehicles desire

9.5.4 Strategies

9.5.4.1 Publisher

Algorithm 1 Publish

```
procedure PUBLISH(p_n, v_n, p_n)
    return b
```

9.5.4.2 Subscriber

9.5.4.3 Forward

9.5.4.4 Matching

9.6 Platoon Recognition

9.6.1 Overview

Platoon recognition is the process of probabilistically recognizing the formation of platoon. This can be realized through a three step process which includes

Algorithm 2 Subscriber

1: **procedure** SUBSCRIBE(p_n, v_n, p_n)
2: **return** b

Algorithm 3 Forward

1: **procedure** FORWARD(p_n, v_n, p_n)
2: **return** b

Identification, Estimation, and Filtering. Platoon identification is the process of identifying the existence of platoons through identifying which, if any, possible candidate vehicles that may belong to a platoon. Platoon estimation involves the estimation of key platoon parameters, which include platoon size, density, viscosity, flow rate, interstatic forces, and lifetime. The final step **of platoon filtering** is the process of finding optimal candidate vehicles which have high likelihood of belonging to a platoon.

9.6.2 Objectives

Global

- Platoon size $L_{platoon}$
- Platoon lifetime $T_{platoon}$
- Platoon density $D_{platoon}$
- Platoon variability $\mathscr{V}_{platoon}$

$$\max_{\{parameter\}} L_{platoon} \tag{1}$$

$$\max_{\{parameter\}} T_{platoon} \tag{2}$$

$$\max_{\{parameter\}} D_{platoon} \tag{3}$$

$$\min_{\{parameter\}} \mathscr{V}_{platoon} \tag{4}$$

Local
Vehicle

Algorithm 4 Matching

1: **procedure** MATCHING(p_n, v_n, p_n)
2: **return** b

- vehicle force v_f
- vehicle communication delay v_{delay}
- vehicle travel time v_{ttime}
- vehicle travel distance $v_{tdistance}$

$$optimize(v_f) \tag{5}$$

$$\min_{\{parameter\}} v_{delay} \tag{6}$$

$$\min_{\{parameter\}} v_{ttime} \tag{7}$$

$$\min_{\{parameter\}} v_{tdistance} \tag{8}$$

9.6.3 Mathematic Notations

- Junctions $j \in \mathscr{J}$
- Roads $r \in \mathscr{R}$
- vehicles $v \in \mathscr{V}$

9.6.4 Metrics

Principle Metrics:

- Platoon Lifetime
- Platoon Size
- Platoon density
- Platoon variability

Vehicle Metrics:

- Vehicle position
- Vehicle velocity
- Vehicle headway
- Vehicle gap

9.6.5 Considerations

Platoons

- Critical Formation decision boundary
- CV Penetration Ratio
- Points of formation
- Points of dissolution
- Points of merging
- Points of splitting
- junction scheduling
- platoon assignment
- platoon regrouping (mid-road)

Road Network

- Road infrastructure
- merging points

9.6.6 Assumptions

9.6.7 Parameters

- Road Capacity
- Platoon Capacity
- Vehicle Length / Size
- inter-platoon distance
- intra-platoon distance

9.6.8 Strategies

9.6.8.1 Grouping

9.6.8.2 States

9.6.8.3 Estimating the Local Vehicle State

9.6.8.4 Identification

9.6.8.5 Estimation

9.6.8.6 Filtering

9.6.8.7 Complete

Algorithm 5 Vehicle State

```
procedure EstimateState(p_n, v_n, p_n)
    return b
```

Algorithm 6 Platoon Identification

```
procedure Identify(p_n, v_n, p_n)                ▷ The g.c.d. of a and b
    I_n ← < p_n, v_n, p_n >
    if I_n ∈ [T_min, T_max] then a
    record I_n
    return b
```

Algorithm 7 Platoon Estimation

```
procedure Estimate(p_n, v_n, p_n)
    return b
```

Algorithm 8 Platoon Filtering

```
procedure Filter(p_n, v_n, p_n)
    return b
```

Algorithm 9 Platoon Recognition

```
procedure Recognize(p_n, v_n, p_n)
    EstimateState(i)
    Identify(i)
    Estimate(i)
    Filter(i)
    return b
```

Table 6: Vehicle States

State	Notation	Value	Description
Following	S_{follow}	0	force pulling vehicles in platoon toward one another
Free Speed	S_{free}	1	Forces which the vehicles desire
Approaching	$S_{approach}$	2	Forces which the vehicles desire
Receding	$S_{receding}$	3	Forces which the vehicles desire

9.7 Platoon Sustainability

9.7.1 Objectives

- Platoon Recognition
- Speed Filtering
- Parameter Estimation

9.7.2 Mathematic Notations

9.7.3 Metrics

9.7.4 Considerations

9.7.5 Assumptions

9.7.6 Parameters

9.7.7 Strategies

Algorithm 10 Platoon Sustainment

```
procedure SUSTAIN(p_n, v_n, p_n)
    return b
```

9.8 Platoon Prediction

9.8.1 Objectives

- Predict future platoon states
- Cooperative path planning

9.8.2 Mathematic Notations

9.8.3 Metrics

9.8.4 Considerations

9.8.5 Assumptions

9.8.6 Parameters

9.8.7 Strategies

9.9 Vehicle Controller

9.9.1 Overview

9.9.2 The Local Control System

9.9.3 Components

Cloud Computing - Paradigms and Technologies

9.10 Platoon Controller

9.10.1 Overview

9.10.2 The Distributed MPC System

9.10.3 Components

9.11 The Complete Controller

9.11.1 Overview

9.11.2 The Complete System

9.11.3 Components

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10 Simulation

10.1 The Environment

10.1.1 Plexe

10.1.2 Veins

10.1.3 Flow

10.1.4 Controls Environment

10.1.5 Environment Manager

10.1.5.1 Shared Memory

10.2 Simulation Parameters

10.3 Scenarios

10.3.1 Overview

A set of scenarios were designed for the testing and validation of the proposed controller, where each set of scenarios tested a different aspect of the controller performance. Each scenario considers three settings for testing which include the single lane setting, the double lane setting, and the multiple lane setting. The single lane setting focuses on the testing and validation of langitudinal control of the vehicle controller The double lane setting focuses on testing the lateral control of the vehicle controller. The multiple lane setting then focuses on the testing and validation of the generalized control performance of the vehicle controller.

The scenarios include the single ring scenario, the extended ring scenario, the grid scenario, the OSM based scenario and finally the randomly generated scenario. Each scenario type provides a unique road structure as to provide a sufficient challenge to a given aspect of the controller. The single ring scenario merely tests the controller on a homogoneous road structure, a single road. The extended ring structure introduces a single junction and tests junction behavior and responses to such "new road structure". The grid scenario tests controller behavior in the presence of multiple junctions. The OSM scenario uses an imported map of a real world road network and tests the controller in such environments. The procedurally generated scenario creates a completely novel and random road network and tests the controller in this highly generalized setting.

10.3.2 Single Ring, Single Lane

-test longitudinal control

10.3.3 Single Ring, Double Lane

-test lateral control

10.3.4 Single Ring, Multi Lane

-test general control

10.3.5 Extended Ring (Junction), Single Lane

- test junction control with longitudinal control

10.3.6 Extended Ring (Junction), Double Lane

- test junction control with lateral control

10.3.7 Extended Ring (Junction), Multi Lane

- test junction control with general control

10.3.8 Grid, Single Lane

- baseline longitudinal control

10.3.9 Grid, Double Lane

- baseline lateral control

10.3.10 Grid, Multi Lane

- baseline general control

10.3.11 OSM, Single Lane

- baseline longitudinal control

10.3.12 OSM, Double Lane

- baseline lateral control

10.3.13 OSM, Multi Lane

- baseline general control

10.3.14 Random Generated, Single Lane

- baseline longitudinal control

10.3.15 Random Generated, Double Lane

- baseline lateral control

10.3.16 Random Generated, Multi Lane

- baseline general control

10.4 Measurements

10.4.1 Overview

10.4.2 Vehicle Speed

10.4.3 Vehicle Headway

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10.4.8 Platoon Density

10.4.9 Platoon Lifetime

10.4.10 Platoon Speed Dispersion

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10.4.13 Platoon Viscosity

10.4.14 Platoon Flow

10.4.15 Platoon Capacity

10.5 Validation

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12 Conclusion

13 Future Work

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A Metric Derivations

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A.2 Platoon Density

A.3 Platoon Lifetime

A.4 Platoon Viscosity

A.5 Platoon Flow Rate

B Proofs

C Simulation Parameters

Part III
Platoon Testing and Analysis

Part IV

Platoon Application

Part V
Platoon Simulation Environment