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1 Truck platooning strategy near merge:
2 Heuristic-based solution and optimality
3 conditions

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Abstract

1
2 Truck platooning aims to form platoon of trucks along freeway corridors to save fuels
3 and increase roadway capacity, but the presence of long platoons is problematic near merges
4 where vehicles from freeway entrance have to make mandatory lane changes. An active pla-
5 tooning strategy that deals with merging of conventional vehicles is needed for platooning
6 application in real world. The paper proposes an original approach to split platoon when
7 approaching merging areas. The proposed strategy aims to provide safe and comfortable
8 merging maneuvers for conventional vehicles while maximizing the efficiency for the truck
9 platoon. This is achieved by deciding the position and time of the truck in the platoon that
10 should open a large gap for merging vehicles. The problem is posed, based on reasonable
11 physical and behavioral assumptions of truck platoon dynamics. A heuristic-based solu-
12 tion is proposed, and its optimality is verified through an optimization-based strategy. The
13 strategy can deal with both individual merging and merging of a small platoon of vehicles.
14 Applicability of the proposed solution is demonstrated via examples.

1 INTRODUCTION

2 Vehicle automation is seen as one of the promising solutions to today's traffic problems since it
3 will revolutionize the way we operate our vehicles today [1]. However, it is also acknowledged
4 that individual automation can hardly bring benefits to collective traffic systems, while their
5 connected automated vehicles (CAV) pose more potential in improving traffic operations [2].

6 Vehicle platooning is a highway CAV application characterized by a string of vehicles
7 keeping short spacing with Vehicle-to-Vehicle (V2V) communication [3, 5, 6]. Vehicle platoon-
8 ing is not a new concept. In the U.S., PATH started the research on automated platoons more
9 than two decades ago, with a public demonstration of vehicle platooning on a special track in
10 San Diego in 1997 [7]. From there onward, PATH continued this line of research and recently
11 experimented a string Cooperative Adaptive Cruise Control vehicles on public highway in 2013
12 [8].

13 As a subclass of vehicle platooning problem, truck platooning has received much at-
14 tention recently. Technically, truck platooning is more challenging compared to car platooning
15 due to the complex truck dynamics. From implementation perspective, truck platooning is more
16 likely to happen before platooning of individual cars due to the pronounced benefits of fuel saving
17 and more mature business models [3]. In Europe, several projects and initiatives were conducted
18 that aimed at putting truck/vehicle platooning on public roads, including the Safe Road Trains for
19 the Environment (SARTRE) project [9], the COMPANION project [10], the Grand Cooperative
20 Driving Challenge (GCDC) [11], and the Truck Platooning Challenge [12]. Truck platooning
21 initiatives have been reported in the U.S. and Japan [13].

22 One of the lessons learned from the existing truck platooning projects is problems that
23 large platoons may bring at freeway entrances and exits [3, 12]. How to handle vehicles merging
24 while long platoons are passing the merging area is an intriguing question for both researchers
25 and practitioners. This work deals with the design of truck platooning strategy at merges to
26 facilitate smooth merging.

27 Relevant work in literature

28 There are many technical challenges with truck/vehicle platooning, including environment per-
29 ception, reliable communication, platooning coordination and vehicle control [1, 4]. In view of
30 platooning coordination and control, several studies discussed the system control architecture
31 involving automated vehicle platoons, most of which pertain to a hierarchical setting [4, 5]. Of-
32 ten a coordination layer is placed between the traffic control layer and the vehicle control layer,
33 dealing with trajectory planning and coordination among platoons [4, 5].

34 Literature has been focusing on vehicle control layer design for platoons. Different con-
35 trol approaches have been used to design vehicle longitudinal control systems. String stability
36 and collision avoidance have attracted considerable attention, addressing the problems of how
37 the controller can attenuate disturbance propagation along the platoon [14] and how to combine
38 vehicle following with collision avoidance mechanism [6].

39 A few researchers have designed maneuver strategies at the coordination layer. A set of
40 protocols for highway maneuvers of platoons was proposed in [15], including platoon merge,
41 platoon split, and lane change. The design of the protocol is based on a finite state description
42 of the platoon maneuvers, giving the commands from the upper level traffic control layer. While

1 acknowledging the pioneering role of this work, the design was not aimed at generating decisions
2 of when and where to split a platoon at highway entrance and was based on fully automated
3 vehicle environment.

4 In [16], entry and exit maneuvers of platoons on highway were discussed. Strategies
5 were proposed that were applicable in highways with dedicated automated vehicle lanes and
6 transitional lanes near entry and exit. The design was based on the assumption that the merg-
7 ing vehicle is a CAV and it required changes of infrastructure, e.g. a parallel transition lane or
8 dedicated ramps, raising concerns over its applicability in reality.

9 In [5], two basic platoon maneuver strategies, merge and split, were proposed to facilitate
10 another automated vehicle joining an existing platoon and a platoon member leaving the platoon
11 respectively. The split strategy was further elaborated by sub-tasks of initiating split request,
12 creating safe gap and changing lane. However, when is optimal to start the gap creation process
13 and how the transient maneuver looks like were not formulated.

14 More recently, a finite state machine approach was also reported in [17] for platoon ma-
15 neuver protocols. The protocols were combined with CACC control logic was used to represent
16 longitudinal behavior. An interesting approach was presented in [18], where a spring-mass-
17 damper analogy was adopted to describe platooning dynamics. This modeling approach allows
18 derivation of efficient platooning strategies at entry and exit by controlling the spring constant
19 and damping coefficient. It can capture different scenarios where an automated vehicle join or
20 leave platoons.

21 Notice that another body of literature focused on platoon formation strategies [19, 20].
22 We restrict the discussion on platoon formation because this paper concentrates on how to split
23 a platoon rather than forming a platoon.

24 Literature shows that quite some effort in defining platoon maneuver protocols at high-
25 way entry and exit. These studies focus on dynamics and interactions between platoons or be-
26 tween a platoon and an individual CAV, which implies communication between interacting pla-
27 toons/vehicles. Some even requires additional changes in the infrastructure, which may impede
28 the near-term application of the strategies. In addition, there is a gap between finite state de-
29 scription of the platoon maneuvers and the detailed operational truck platooning strategies for
30 the transition between states. In case of truck platooning, it is likely that the platoon has to be de-
31 tached to facilitate merging vehicles at on-ramp sections. A decision-making strategy to support
32 when and where to split the truck platoon is yet to be explored.

33 To this end, the paper proposes an original approach to split platoon approaching merg-
34 ing areas. The split strategy aims to provide safe and comfortable merging maneuvers while
35 restricting the disturbance for the platoon. The problem is posed, based on reasonable physical
36 and behavioral assumptions about string-stable vehicle following dynamics. A heuristic-based
37 solution and optimization-based solution are proposed based on simplified car-following model
38 for platoons, which enables us deriving the vehicle index and time to yield a gap analytically.
39 The performance of the strategies is verified with simulation.

40 In the remainder of the paper, we first present the vehicle-following model for platoons,
41 followed by the formulation of the decision-making strategy and its optimality verification. After
42 that, we apply the strategy to derive some insights into the relations between model parameters.
43 We summarize the findings and future research in the conclusion section.

1 **MODEL FOR PLATOON DYNAMICS NEAR MERGE**

2 **Vehicle-following model**

Vehicle trajectories are described by a Vehicle-Following model, also referred to as Car-Following (CF) model. In the paper, we assume the design of longitudinal vehicle control algorithm guarantees string stability of the truck platoon and the Newell model is considered [21] for the CF model. It consists in a piece-wise linear speed-headway relationship, which is consistent with the macroscopic kinematic wave model originally proposed in [22, 23]. Several arguments are in favor of this model for the study : simple but not simplistic representation of first-order platoon dynamics; limited number (three) and observability of model parameters; ability to describe car-following steady states; numerous prior works on vehicle trajectory-based calibration and validation. In the paper, the model is supposed to describe the platoons steady states, *i.e.* when the platoon is formed with no disturbance to the trucks time-gap policy. It assumes that under normal car-following situations, the speed of the following truck is adjusted with respect the distance to its leader. The speed-headway relationship is defined based on three parameters: u the free-flow speed, w the maximum wave speed and κ .

$$v_i^{t+1} = \min \left(u, \left(s_i^t - \frac{1}{\kappa} \right) \cdot w \cdot \kappa \right) \quad (1)$$

Notice that the minimum time headway h is determined as follows :

$$h = \frac{1}{\kappa} \cdot \frac{w + u}{w \cdot u} \quad (2)$$

3 Also notice that from a physical perspective :

- 4 - κ is directly related to the minimum spacing at stop $s_x = 1/\kappa$ (including the truck length).
- 5 - $r=1/(w \cdot \kappa)$ is the reaction time, *i.e.* a speed variation of the leader will impact the follower trajectory with a time shift r .

7 The car-following behavior can be completed with two additionnal models. First, an acceleration model which bounds the acceleration with a maximum value a_x [24]. Second, a relaxation model [25, 26] which describes the speed difference ε that a follower is willing to accept when its spacing is lower that its equilibrium value. The complete CF model can adress most of the car-following situations with a minimal set of five parameters.

12 **Parameters for platooning under constant-time-gap policy**

All the five parameters have a physically meaning and default values can easily be proposed. The literature provides many references to refine their calibration, mostly based on empirical trajectories [27, 28]. To the best of authors knowledge, the proposed CF-model has never been calibrated for truck platooning operations. Here we propose basic formulas to calibrate the car-following parameters according to the platooning strategy.

Classically, a Truck-Platooning (TP) strategies consider a target gap g , which can be expressed in time (g^t) (e.g. the constant time gap policy) or in space (g^s) (e.g. the constant spacing policy). The gap corresponds to the time or space difference between the front bumper of the following current truck and the rear bumper of its leader. In the remaining we consider the time gap, but identical results can be drawn by considering the space gap instead.

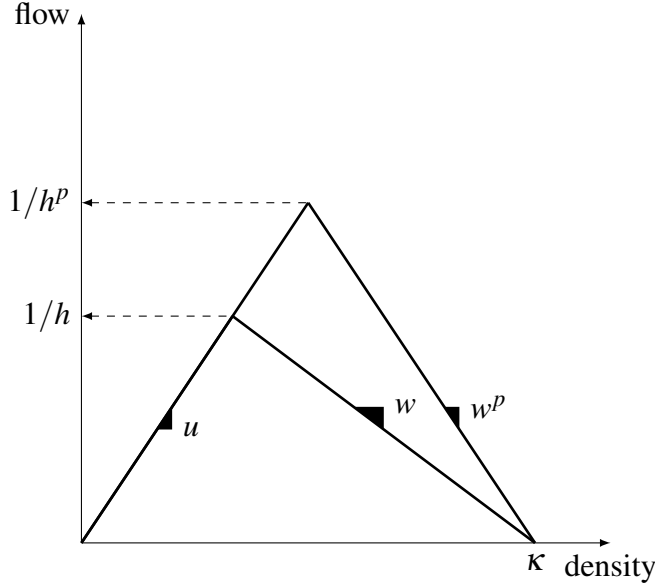


Figure 1: Fundamental diagram

The speed-spacing function of the CF model has to be calibrated with respect to this gap. In the case of the Newell CF model, only 3 parameters are concerned: u ; w and κ . However, u is classically related to the maximum authorized speed on the section, and κ is constrained by the length of the vehicle L . Consequently, the maximum wave speed w is the parameter to be adjusted according to the TP strategy.

Considering the length of a truck L and the minimum time gap g^t , the minimum time headway during truck platooning operation writes:

$$h^p = g^t + L/u \quad (3)$$

the corresponding space headway is $s^p = u \cdot g^t + L$. Thus, the maximum wave speed adjusted for TP strategy becomes :

$$w^p = \frac{u}{u \cdot \kappa \cdot (g^t + L/u) - 1} \quad (4)$$

Notice that this equation holds if $u \cdot \kappa \cdot (g^t + L/u) > 1$. Consequently the minimum gap g has to respect the following constraint:

$$g^t > \frac{1}{u} \cdot \left(\frac{1}{\kappa} - L \right) \quad (5)$$

1 This condition imposes a minimum gap between trucks according to their car-following properties.
2

3 **Remark** It should be noted that under platooning operation, the reaction time $r^p = 1/(w^p \cdot \kappa)$
4 of truck is (or should be) highly decreased by the raising of its maximum wave speed.

1 Platoon dynamics due to merge

2 When a vehicle is about to merge from the on-ramp, a truck will decrease its speed to open a gap
 3 for the merging vehicle. We propose to process the speed of the complying truck considering
 4 relaxation. Thus, the complying truck will accept a speed lower than its leader, such that the gap
 5 will progressively increase. It provides the advantage of simplicity, it accounts for the speed of
 6 the leading truck and it rely on a two physical parameters:

- 7 • ε , the speed difference with the predecessor during the relaxation period
- 8 • a_x , the maximum acceleration rate at the end of the relaxation period.

9 .
 The CF model is modified accordingly and the different model formulations from [24,
 25, 26, 28] can be combined as follow:

$$v_i^{t+1} = \min(v_{i,dem}^{t+1}, v_{i,sup}^{t+1}) \quad (6)$$

where

$$\begin{cases} v_{i,dem}^{t+1} = \max(u, v_i^t + a_x \cdot dt) \\ v_{i,sup}^{t+1} = \begin{cases} v_{i-1}^t - \varepsilon & \text{if relaxation is active} \\ (s_i^t - \frac{1}{\kappa}) \cdot w \cdot \kappa & \text{if not} \end{cases} \end{cases} \quad (7)$$

10 Note that the time step must be set as : $\delta t = 1/w \cdot \kappa$. The process is illustrated in Figure
 11 2. On the left side, the platoon is composed of 10 trucks crosses the stretch of road at the free
 12 flow speed $u = 20\text{m/s}$ with a constant time gap $g^p = 0.5$ s between every trucks. On the right
 13 side on the figure, the fifth truck ($I_n = 5$) decreases its speed between $t = 30\text{s}$ and $t = 60\text{s}$, with
 14 a speed difference $\varepsilon = 1\text{m/s}$. Then the truck re-accelerate at the rate a_x to retrieve the free-flow
 15 speed. During this period, a gap is formed and the final spacing headway between the forth and
 16 fifth trucks reaches $s = 60\text{m}$.

17
 18 At this stage, some issues are raised. How to choose the truck that must comply by
 19 decreasing its speed? How to estimate the starting time of the complying maneuver? These
 20 problems are posed and analytical (heuristic) solutions are proposed in the next section.

21 DESIGN OF PLATOON SPLIT STRATEGY

22 Without anticipation of merging maneuvers, the presence of platoons involves safety issues and
 23 traffic disturbances. In Figure 2, a platoon of 10 trucks crosses a road stretch (3km). A vehicle
 24 merges at the time-position $t = 60\text{s}, x = 1000\text{m}$ (trajectory not represented for a better readability).
 25 On the left picture, the platoon does not anticipate the merging maneuver: the vehicle
 26 merges in a short space, which raises comfort and safety issues, and immediate following truck
 27 behind the merging vehicle may over-react and trigger disturbance for the surrounding traffic.
 28 On the right picture, the platoon anticipates the merging maneuver : the seventh truck decreases
 29 its speed far upstream the merge, so that a gap is created. The vehicle merges in comfortable and
 30 safety conditions, and the disturbance for surrounding traffic on the carriageway is smoothed.

31 The main objective of the platoon strategy is to determine the truck index in the platoon
 32 that should yield a gap for the merging vehicle, denoted by i^{yield} and the time instant that the

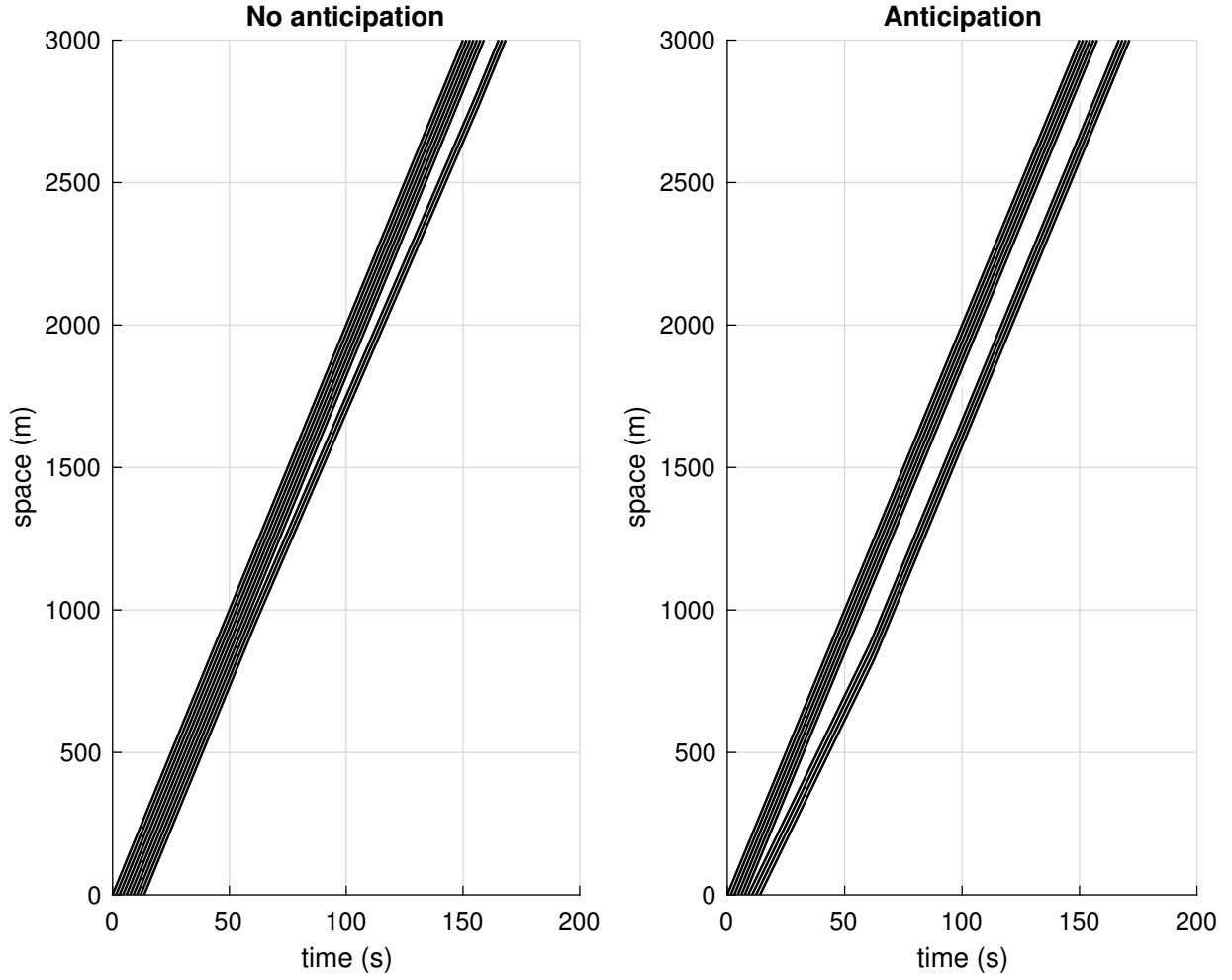


Figure 2: Platoon trajectories without splitting (left) and with splitting (right)

1 gap creation process starts, denoted by t^{yield} in real time, so that merging vehicles can merge
 2 smoothly onto the main carriageway. Thus the decision variables are: $\mathbf{d} = (t^{\text{yield}}, T_a)$.

3 **Operational assumptions**

4 The design of the platooning strategy at merges is based on several assumptions. In particular,
 5 we assume that:

- 6 • trucks in the platoon follow their leader with a constant time gap g^t , corresponding to
 7 a time headway $h^p = g^t + L/u$;
- 8 • conventional vehicles from on-ramp merge at the same speed of the platoon, denoted
 9 u ;
- 10 • the truck platoon leader has the knowledge of the time t^{merge} that the merging vehicles
 11 start to move to the main carriageway from the acceleration lane. This can be assisted by a
 12 roadside system that detects the position and speed of the merging vehicle;
- 13 • the truck platoon leader decides which truck in the platoon should open a gap to ac-

1 accommodate the merging vehicles and when it should do so. Trucks in the platoon follow the
2 decisions of the truck platoon leader;

- 3 • the acceleration for trucks is bounded, denoted a_x ;
- 4 • the merging is performed in a relatively smooth way, e.g. no emergency braking will be
5 needed for the trucks and merging cars. The merging process model is described in the previous
6 section.

7 **Heuristics-based strategy**

8 The problem is posed in Figure 3, and a heuristic solution is proposed to estimation the estimating
9 the yielding truck index i^{yield} , the anticipation time T_a and the speed difference ε . Recipes for
10 each variable to estimate are presented in paragraphs below.

11 *Solution for i^{yield}*

We start with the heuristic method that based on the *first-in-first-out* (FIFO) principle, i.e. for all
vehicles involved in the merging process, the passing sequence at the merging point is determined
by the predicted arrival time t_i^{arrive} at the fixed merging point X_m . The arrival time is determined
by the *constant speed heuristics*, i.e. vehicles will maintain their current speed in the near future,
thus we have:

$$t_i^{arrive}(t) = \frac{X_m - x_i(t)}{v_i(t)} \quad (8)$$

Thus we can determine the yielding truck index (increasing in the upstream direction) as:

$$i^{yield} = i \in \left[t_{i-1}^{arrive}(t) < T_m < t_i^{arrive}(t) \right] \quad (9)$$

12 Since the truck index in the platoon is an ordered set, the uniqueness of the solution (9) is guar-
13 anteed.

14 *Solution for T_a*

After determining the yielding vehicle index, the time that the truck starts to yield must be deter-
mined. Some empirical evidence shows that it takes around 20 to 40 seconds for a truck to split
from a platoon [9]. This is consistent with the duration of relaxation process after merge [28].
Thus we choose to command the designated truck starting to yield gap at the time T^{yield} before
the merging vehicle moves onto the mainline:

$$T^{yield} = T_m - T_a \quad (10)$$

15 where T_a is the anticipation time before the merging maneuvers. The objective is to formulate
16 anticipation time with respect the to decision variables, i.e. the time that a truck needs to decrease
17 their speed to open a gap $[T^{yield}, t_1]$, and then to accelerate to come back to its initial speed $[t_1, T_m]$.
18

Figure 3 shows that two time periods have to be considered separately.

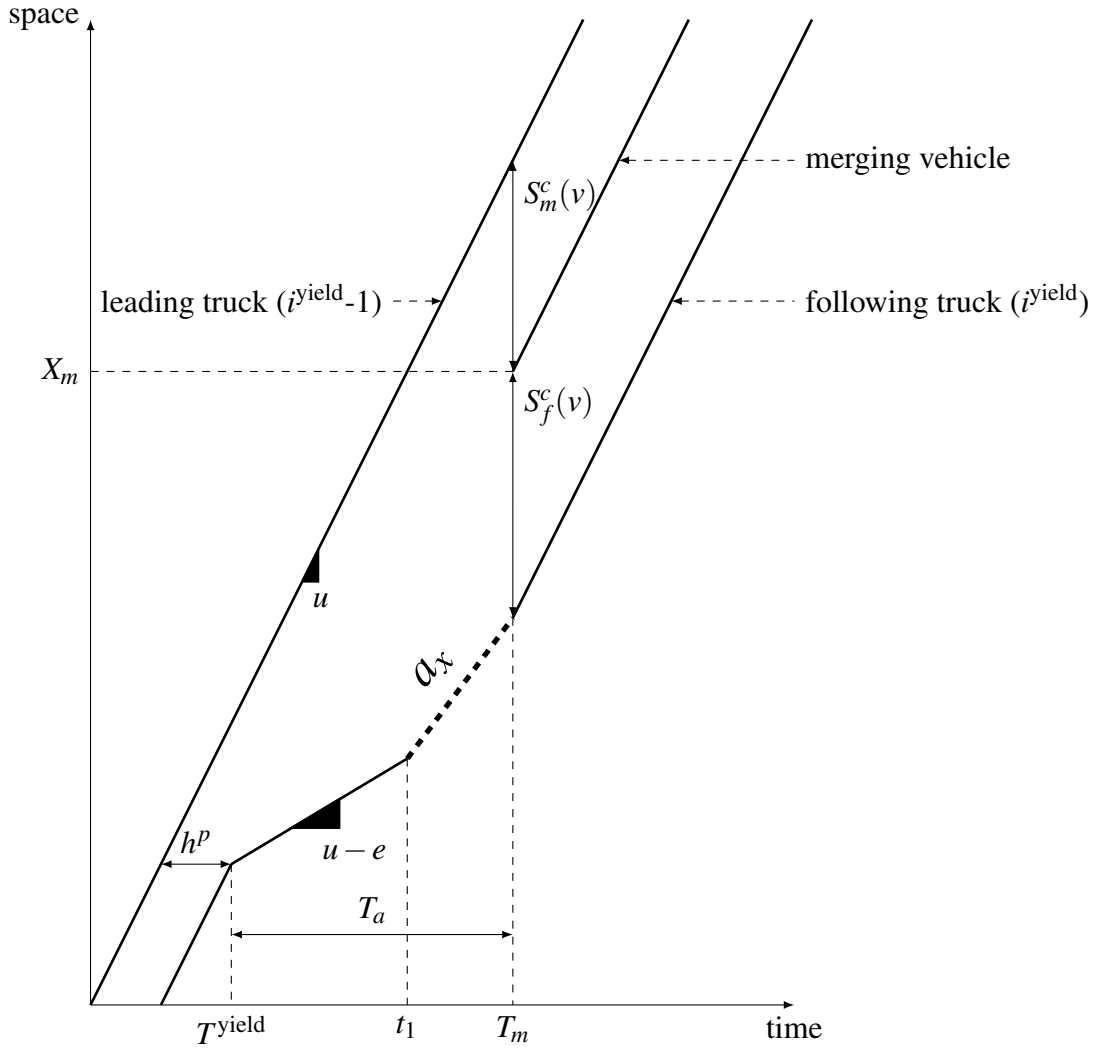


Figure 3: Heuristic-based decision : problem and parameters

Recipe for t_1 During the acceleration period, the following truck accelerates from the speed $u - \epsilon$ to reach the free-flow speed u . Assuming a constant acceleration rate a_x , it gives:

$$t_1 = T_m - \frac{\epsilon}{a_x} \quad (11)$$

Recipe for T^{yield} From Figure 3

$$u \cdot (g^t + T_a) = (u - \epsilon) \cdot (t_1 - T^{\text{yield}}) + \int_{t_1}^{T_m} \int_{t_1}^{T_m} a_x \cdot dt + S^c \quad (12)$$

where $S^c = S_m^c(v) + S_f^c(v)$. It follows from Equations 11 and 12 that:

$$T_a = \frac{S^c - h^p \cdot u}{\varepsilon} + \frac{\varepsilon}{2 \cdot a_x} \quad (13)$$

1 Solution for ε

In the previous section, the optimal anticipation time is the decision variable to set, assuming a given ε . However, in reality, the platoon maybe be informed of the merging time from a road side unit, where the only decision variable is the speed difference ε . Consequently, the problem is re-formulated to find the optimal ε for a given anticipation time $T_a = T_m - T^{\text{yield}}$. To solve this problem, Equation 13 gives:

$$\begin{aligned} \frac{\varepsilon}{2 \cdot a_x} - T_a + \frac{S^c - h^p \cdot u}{\varepsilon} &= 0 \\ \Leftrightarrow \frac{\varepsilon^2}{2 \cdot a_x} - T_a \cdot \varepsilon + (S^c - h^p \cdot u) &= 0 \end{aligned} \quad (14)$$

A positive solution exists for Equation 14 if (and only if) $T_a > \sqrt{\frac{2 \cdot (S^c - h^p \cdot u)}{a_x}}$. The solution is:

$$\varepsilon^+ = a_x \cdot T_a \cdot \left(1 - \sqrt{1 - \frac{2 \cdot (S^c - h^p \cdot u)}{T_a^2 \cdot a_x}} \right) \quad (15)$$

Equation 15 is easy to implement, but the importance of each parameter is not explicit. We propose to derive a second order Taylor expansion to bring out high (first order) and low (second order) importance parameter.

$$\begin{aligned} \hat{\varepsilon} &= \frac{S^c - h^p \cdot u}{T_a} + \frac{1}{2} \cdot \frac{(S^c - h^p \cdot u)^2}{T_a^3 \cdot a_x} \\ &= \frac{S^c - h^p \cdot u}{T_a} \left(1 + \frac{1}{2} \cdot \frac{S^c - h^p \cdot u}{T_a^2 \cdot a_x} \right) \end{aligned} \quad (16)$$

2 Equation 16 demonstrate that the anticipation time T_a plays a major role while the acceleration
3 rate a_x has a minor impact on ε .

4 It should be noted here that S is a critical spacing composed of $S_m^c(v)$, critical space head-
5 ways for the merging vehicle, and $S_f^c(v)$, critical spacing for the following truck. The solution can
6 be easily adapted for multiple merging maneuvers, when a platoon of N vehicles needs to merge
7 on the carriageway. In this case, The solution basically considers the critical spacing for a platoon
8 of N vehicles $S^c(v, N) = N \cdot S^c(v)$. Then the critical spacing S^c becomes: $S^c = S_n^c(v, N) + S_f^c(v)$.

9 Equivalence to an optimization-based strategy

10 In this section, we show that the heuristic-based solution is equivalent to an optimization-based
11 strategy. Recall the general objective of the platoon split strategy: opening a sufficient gap within
12 a closely-spaced truck platoon to facilitate comfortable merging of conventional vehicles from

1 on-ramp. To this end, we formulate the problem as the following mathematical programme, with
 2 objective function:

$$\max_{i^{yield}, t^{yield}} \sum_{j=1}^N q_j^{T_m} \equiv \max_{i^{yield}, t^{yield}} \sum_{j=1}^N \frac{v_j^{T_m}}{s_j^{T_m} + L} \quad (17)$$

3 where N is the total number of trucks in the platoon and $q_i(T_m)$ is the *local flux* for vehicle i .

4 The optimal decisions are subject to some physical and behavioral constraints, including:

5 • The car-following dynamics in normal conditions, for truck platoons and during merg-
 6 ing, see Section 2.

• Safe merge: at the time of merge, the yielding truck should keep a spacing with respect to the merging vehicle no less than the normal vehicle- following spacing:

$$s_{i^{yield}}^{T_m} \geq s^t \quad (18)$$

• Bounds on speed: the vehicle speeds are bounded by the zero speed and free speed u ;

$$0 \leq v_i(t) \leq u \quad (19)$$

• Limited acceleration capability;

$$\dot{v}_i(t) \leq a_x \quad (20)$$

7 The formulation entails that the optimal maneuver strategy aims at maximizing the flux
 8 at the time of merging while respecting physical and behavioral constraints.

Notice that the objective function can be rewritten as:

$$\sum_{j=1}^N \frac{v_j^{T_m}}{s_i^{T_m} + L} = \sum_{j=1}^{i^{yield}} \frac{1}{g^t + L/u} + \frac{v_{i^{yield}}^{T_m}}{s_{i^{yield}}^{T_m} + L} + \sum_{j=i^{yield}+1}^N \frac{1}{g^t + L/v_j} \quad (21)$$

9 The first term in the right hand side (RHS) of Equation 21 is at its maximum flux since
 10 $v_j \leq u$ and we would like as many truck passing the merging vehicle as possible. But the safety
 11 constraint restricts the number to the first truck in the platoon that would arrive at the merging
 12 point later than the merging vehicle at the maximum speed u . This gives the same solution for
 13 i^{yield} as in Equation 9. The third term in the RHS of 21 is a decreasing function of v_j and achieves
 14 the maximum when $v_j = u$.

15 The middle term in the RHS of 21 depends on the yielding time t^{yield} . Let $\bar{t}^{yield} = T^{yield} +$
 16 δ , where T^{yield} is determined by the heuristic method. If $\delta > 0$, using the same derivation process
 17 as in the heuristic-based method, the spacing of the yielding truck at the time of merge will
 18 become $s^{yield} = s_f + u \cdot \delta$, while the speed of the yielding truck and those behind the yielding
 19 truck at the time of merge is the same as u . Thus the third term of the objective function achieves
 20 its maximum but the middle term is smaller than that from the heuristic solution: e.g. $\frac{u_i}{s_f + u\delta + L} <$
 21 $\frac{u}{s_f + L}$.

1 When $\delta < 0$, we can only achieve $s^{yield} = s_f$ when the acceleration adopted by the yielding truck
 2 i^{yield} is less than a_x . This implies the speed of the yielding truck at the time of merge is lower
 3 than free speed: $v_{i^{yield}}^{T_m} < u$, and the second and third term becomes: $\frac{v_{i^{yield}}^{T_m}}{s_f + L} + \sum_{j=i^{yield}}^N \frac{1}{g^t + L/v_{i^{yield}}}$ <
 4 $\frac{u}{s_f + L} + \sum_{j=i^{yield}}^N \frac{1}{g^t + L/u}$, which is smaller than that with the heuristic solution. Consequently, we
 5 can conclude that *the heuristics-based solution is the optimal solution that maximize the flux at*
 6 *the time of merging conditioned at providing sufficient gap for the conventional vehicle to merge.*

7 APPLICATION

8 *Illustrative example*

9 Let consider the following situation:

- 10 • a platoon is composed of 10 trucks, moving with a speed $u = 20m/s$ with a time gap
11 policy is $g^t = 1s$.
- 12 • a merging maneuver has the following parameters : $V_m = u = 20m/s$ and the merging
13 time $T_m = 60s$.
- 14 • in case of merging, the yielding truck opens the gap with speed difference of $\varepsilon = 2m/s$
15 and then with acceleration at $a_x = 1m/s^2$.

16
 17 Figure 4a illustrates vehicle trajectories with no anticipation (left) and with the optimal
 18 anticipation maneuver (right). According to the heuristic-based strategy proposed in the paper,
 19 the optimal solution is : $i^{yield} = 8$, $T_a = 48s$. On the right picture, the eighth truck in the platoon
 20 starts to decrease its speed at the time $t = T^{yield} = 12s$ from $20m/s$ to $18m/s$. It keeps this speed
 21 to open the gap until the time $t_1 = 58s$, and it accelerates at the rate $a_x = 1m/s^2$ to return to
 22 its free-flow speed. The variation of the space headway with respect to time is illustrated in
 23 Figure 4c, where the space headway is gradually increased from $h = 40m$ to $h = 125m$ during
 24 the yielding maneuver. Finally, at the time $t=60s$, the space headway has reached $h = 125m$, *i.e.*
 25 $105m$ excluding the truck length.

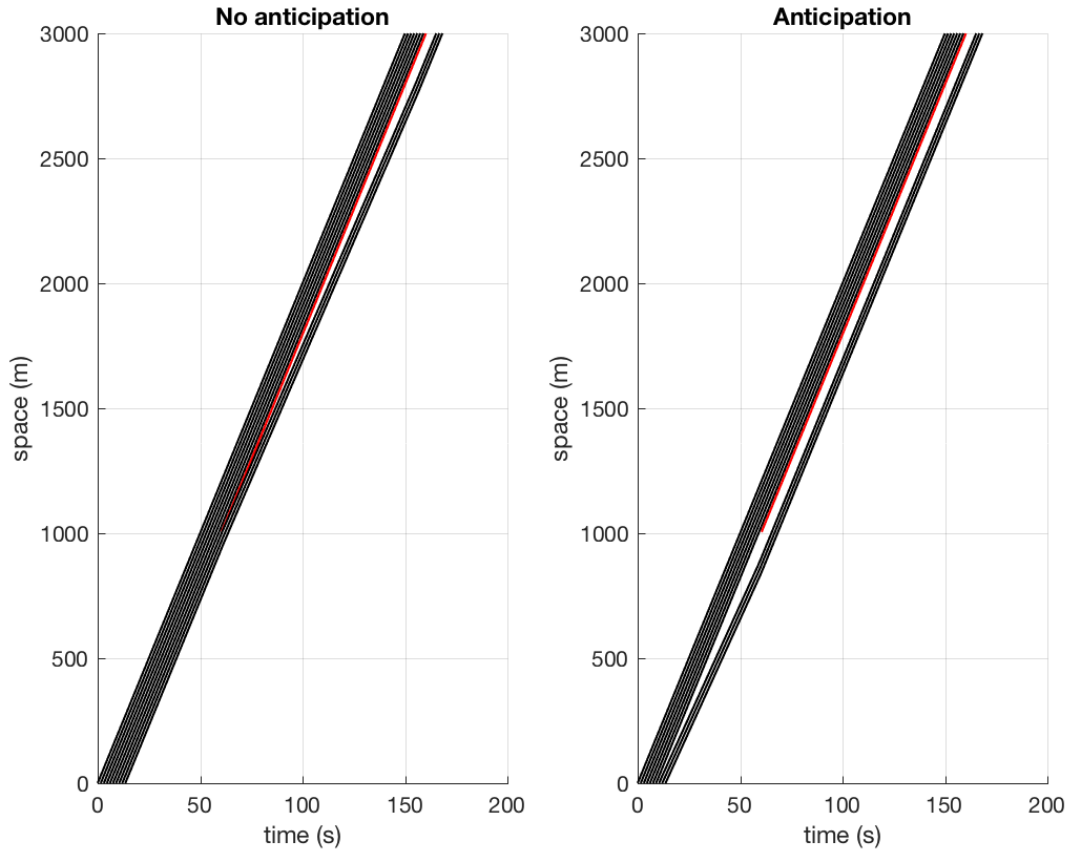
26 *Decision support chart*

27 The heuristic-based solution can be the basis for designing decision support diagrams. Let as-
 28 sume that a platoon of trucks received the following merging information from a road site unit :
 29 "a vehicle will merge in 50s from the next on-ramp". With the help of Figure 5(a), the truck will
 30 start its maneuvers immediately with a speed difference $\varepsilon = 2m/s$. The decision can be adjusted
 31 according to the number of vehicle to merge (See Figure 5) and the maximum acceleration rate
 32 a_x of the truck.

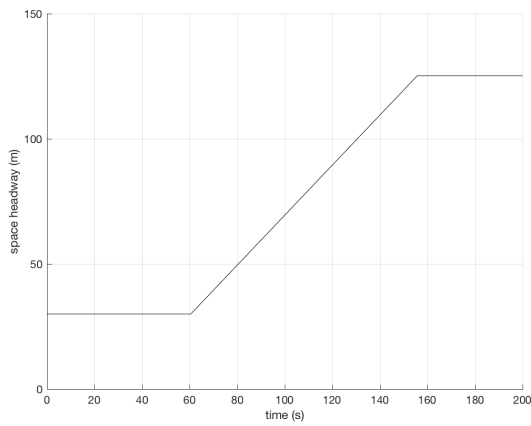
33 *Impact on traffic*

34 It should be noted that the anticipation maneuver smooths the impact of merging maneuvers
 35 inside platoon of truck. It should also be noted that the anticipation limits the impact on traffic
 36 flow. Indeed, total travel time or total delay for trucks does not depend on the transitional yielding
 37 parameters, but it only depends on the number of vehicle(s) that merge, which causes a short
 38 delay to the trucks that follows the merging vehicle(s).

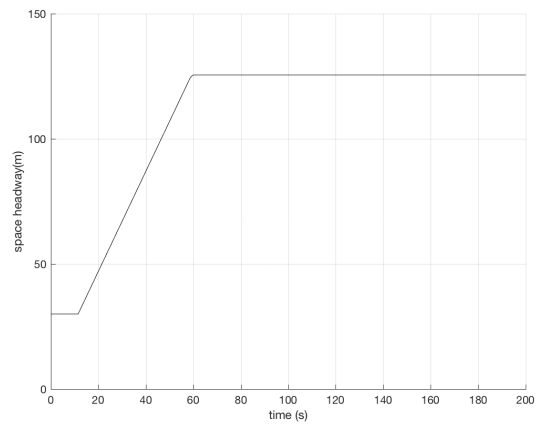
39 On the contrary, if the merging maneuvers are not anticipated by platoons, one can expect



(a)



(b)



(c)

Figure 4: Platoon trajectories without anticipation (left) and with the heuristic-based decision (right)

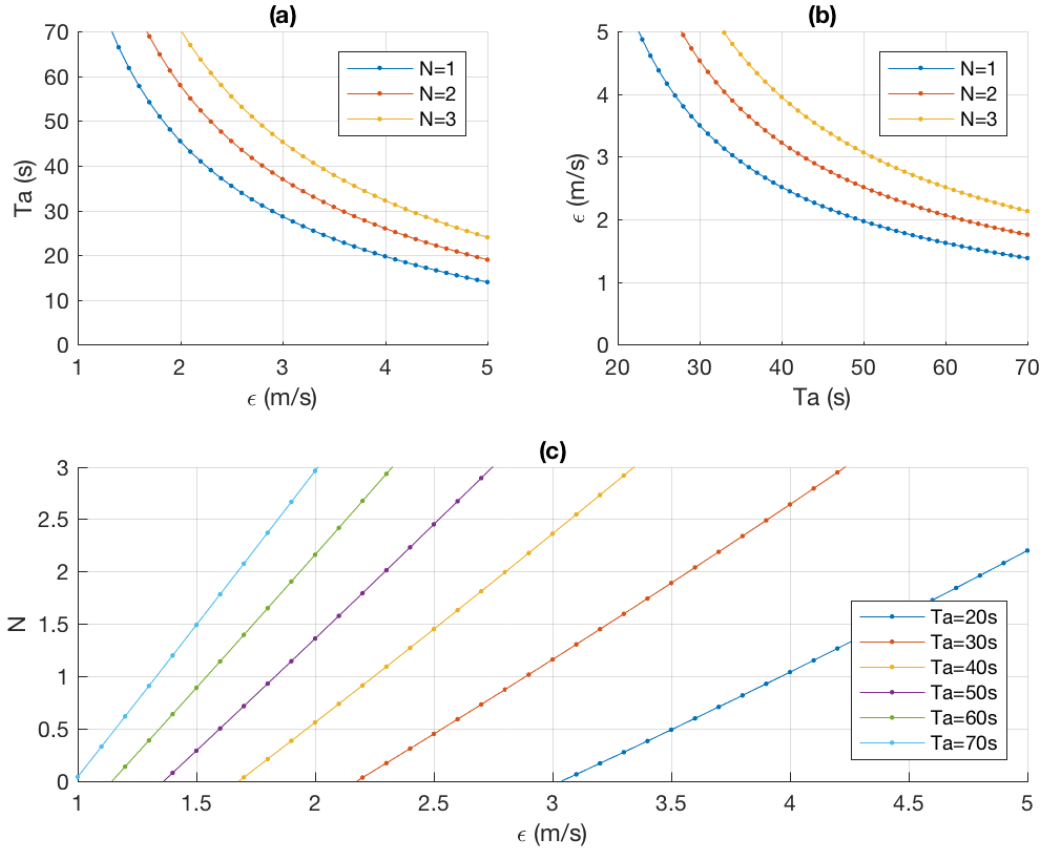


Figure 5: Decision support charts for adapting (a) anticipation time $T_a = f(\epsilon, N)$, (b) speed difference $\epsilon = f(T_a, N)$ or (c) number of vehicle(s) to merge $N = f(N, T_a)$

- 1 merging failures with vehicles stopped at the end of the acceleration lane, or an abrupt deceleration
- 2 and over reactions from following trucks. Both cases are known to be the cause of capacity
- 3 drop around merges, with major impact on traffic conditions.

4 CONCLUSION

5 Main contribution

- 6 The paper proposes an original solution to split platoon of trucks approaching merging areas.
- 7 The splitting aims to provide a safe and comfortable merging maneuvers while restricting the
- 8 disturbance on the carriageway. The problem is posed, based on reasonable physical and behav-
- 9 iorual assumptions. A heuristic-based solution is proposed, which optimizes the flux at the time
- 10 of merging while supplying safe gap for the merging vehicles. The proposed solution can be the
- 11 basis for designing efficient and safe splitting strategies for platoons. The paper also provides de-
- 12 cision support charts that can be the basis for scaling the anticipation time or the speed difference
- 13 of trucks with respect to the number of vehicle(s) to merge.

1 **Further research**

2 In the paper, the solution is adapted to platoons of vehicles from the on-ramp merges into a
3 platoon of trucks on the main line. Further research is needed to extend the proposed solution
4 to address several independent merging vehicles. Moreover, it is assumed that vehicles merge
5 at the speed of the platoon, which could be extended for low speed merging maneuvers. And
6 finally, the proposition can be the basis for advanced solutions, where the anticipation time can
7 be combined with a merging control, for instance with ramp-metering strategies. The ramp
8 metering algorithm would control the rate and the speed of the merging maneuvers, and would
9 provide more flexibility framework to improve global safety and comfort indicators, for both
10 trucks and light vehicles.

References

- [1] S. E. Shladover, "Automated vehicles for highway operations (automated highway systems)," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 219, no. 1, pp. 53–75, 2005.
- [2] S. E. Shladover, C. Nowakowski, X.-Y. Lu, and R. Ferlis, "Cooperative adaptive cruise control," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2489, pp. 145–152, 2015.
- [3] C. Nowakowski, D. Thompson, S. E. Shladover, A. Kailas, and X.-Y. Lu, "Operational concepts for truck maneuvers with cooperative adaptive cruise control," *Transportation Research Record: Journal of the Transportation Research Board*, no. 2559, pp. 57–64, 2016.
- [4] P. Varaiya, "Smart cars on smart roads: problems of control," *IEEE Transactions on Automatic Control*, vol. 38, pp. 195–207, Feb 1993.
- [5] S. Halle, J. Laumonier, and B. Chaib-Draa, "A decentralized approach to collaborative driving coordination," in *Proceedings of the 7th International IEEE Conference on Intelligent Transportation Systems*, pp. 453–458, Oct 2004.
- [6] M. Wang, W. Daamen, S. P. Hoogendoorn, and B. van Arem, "Cooperative car-following control: Distributed algorithm and impact on moving jam features," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, pp. 1459–1471, May 2016.
- [7] R. Rajamani, H.-S. Tan, B. K. Law, and W.-B. Zhang, "Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons," *IEEE Transactions on Control Systems Technology*, vol. 8, pp. 695–708, Jul 2000.
- [8] V. Milanés, S. E. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, "Cooperative adaptive cruise control in real traffic situations," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, pp. 296–305, Feb 2014.
- [9] C. Bergenhem, Q. Huang, A. Benminmoun, and T. Robinson, "Challenges of platooning on public motorways," in *17th World Congress on Intelligent Transportation Systems*, 2010.
- [10] A. Alam, B. Besselink, V. Turri, J. Martensson, and K. H. Johansson, "Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency," *IEEE Control Systems*, vol. 35, pp. 34–56, Dec 2015.
- [11] E. van Nunen, R. Kwakkernaat, J. Ploeg, and B. Netten, "Cooperative competition for future mobility," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, pp. 1018–1025, Sept 2012.
- [12] Rijkswaterstaat, "European truck platooning challenge 2016: Lessons learnt," 2016.
- [13] S. Tsugawa, S. Jeschke, and S. E. Shladover, "A review of truck platooning projects for energy savings," *IEEE Transactions on Intelligent Vehicles*, vol. 1, pp. 68–77, March 2016.

- 1 [14] J. Ploeg, N. van de Wouw, and H. Nijmeijer, " L_p string stability of cascaded systems:
2 Application to vehicle platooning," *IEEE Transactions on Control Systems Technology*,
3 vol. 22, no. 2, pp. 786–793, 2014.
- 4 [15] A. Hsu, F. Eskafi, S. Sachs, and P. Varaiya, "Protocol design for an automated highway
5 system," *Discrete Event Dynamic Systems*, vol. 2, pp. 183–206, Feb 1993.
- 6 [16] D. N. Godbole, F. Eskafi, E. Singh, and P. Varaiya, "Design of entry and exit maneuvers
7 for ivhs," in *American Control Conference, Proceedings of the 1995*, vol. 5, pp. 3576–3580
8 vol.5, Jun 1995.
- 9 [17] M. Amoozadeh, H. Deng, C.-N. Chuah, H. M. Zhang, and D. Ghosal, "Platoon management
10 with cooperative adaptive cruise control enabled by vanet," *Vehicular Communications*,
11 vol. 2, no. 2, pp. 110 – 123, 2015.
- 12 [18] S. Bang and S. Ahn, "Platooning strategy for connected and automated vvehicle: Transition
13 from light traffic," *Transportation Research Record*, 2017.
- 14 [19] R. Hall and C. Chin, "Vehicle sorting for platoon formation: Impacts on highway entry
15 and throughput," *Transportation Research Part C: Emerging Technologies*, vol. 13, no. 5,
16 pp. 405 – 420, 2005.
- 17 [20] M. Saeednia and M. Menendez, "Analysis of strategies for truck platooning," *Transporta-
18 tion Research Record: Journal of the Transportation Research Board*, vol. 2547, pp. 41–48,
19 2016.
- 20 [21] G. F. Newell, "A simplified car-following theory: a lower order model," *Transportation
21 Research Part B: Methodological*, vol. 36, no. 3, pp. 195–205, 2002.
- 22 [22] M. J. Lighthill and G. B. Whitham, "On kinematic waves. ii. a theory of traffic flow on long
23 crowded roads," *Proceedings of the Royal Society of London A: Mathematical, Physical
24 and Engineering Sciences*, vol. 229, no. 1178, pp. 317–345, 1955.
- 25 [23] P. I. Richards, "Shock waves on the highway," *Operations research*, vol. 4, no. 1, pp. 42–51,
26 1956.
- 27 [24] L. Leclercq, "Bounded acceleration close to fixed and moving bottlenecks," *Transportation
28 Research Part B: Methodological*, vol. 41, no. 3, pp. 309–319, 2007.
- 29 [25] L. Leclercq, N. Chiabaut, J. Laval, and C. Buisson, "Relaxation phenomenon after lane
30 changing: Experimental validation with ngsim data set," *Transportation Research Record:
31 Journal of the Transportation Research Board*, no. 1999, pp. 79–85, 2007.
- 32 [26] J. A. Laval and L. Leclercq, "Microscopic modeling of the relaxation phenomenon using
33 a macroscopic lane-changing model," *Transportation Research Part B: Methodological*,
34 vol. 42, no. 6, pp. 511–522, 2008.

- 1 [27] A. Duret, C. Buisson, and N. Chiabaut, “Estimating individual speed-spacing relationship
2 and assessing ability of newell’s car-following model to reproduce trajectories,” *Trans-*
3 *portation Research Record: Journal of the Transportation Research Board*, no. 2088,
4 pp. 188–197, 2008.
- 5 [28] A. Duret, S. Ahn, and C. Buisson, “Passing rates to measure relaxation and impact of lane-
6 changing in congestion,” *Computer-Aided Civil and Infrastructure Engineering*, vol. 26,
7 no. 4, pp. 285–297, 2011.