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On-ramp traffic merging using cooperative intelligent vehicles: a slot-based approach

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Abstract— **The merging of main road and on-ramp traffic is known to lead to congestion under heavy traffic conditions. This is mainly due to the underutilization of the road infrastructure and the lack of efficiency in the way the in which the merging manoeuvre is performed by human drivers. We propose a merging algorithm based on our previous work on slot-based driving which employs cooperation between vehicles within the main motorway as well as between motorway and on-ramp vehicles to achieve a highly efficient merging. The results of the evaluation show that our algorithm achieves a very high throughput and low delay on the on-ramp and clearly outperforms the merging performed by VISSIM's human driver model.**

I. INTRODUCTION

In the context of a global economy that is becoming increasingly reliant on just-in-time production and distribution systems, reliable road transportation plays a very important role. More specifically, these systems depend on highly accurate total journey time estimations [1]. The main problem in accurately predicting motorway journey times lies in the unpredictability of traffic congestion and its impact on the total duration of a journey. Preventing congestion is therefore a task of significant importance.

The fundamental diagram of traffic flow shows that when a critical traffic density is reached the flow becomes unstable, ultimately causing congestion. This has lead to the common belief that, because congestion is caused by traffic demand exceeding the capacity of the highway, the way to prevent congestion is by extending the network of roads. However, Shladover [2] has shown that, due to the necessary safety margins between vehicles, the utilization of the roadway infrastructure is at best 5% of the total surface of the motorway. Furthermore, Chen et al. [3] argue that the main cause of congestion is the inefficient operation of motorways during periods of high demand. All of these are ultimately consequences of the limitations of human drivers, such as slow reaction times and the competitive rather than cooperative nature of human driving [4]. As such, traffic congestion is first of all a consequence of the limitations of human drivers.

Unfortunately, in the past, little could be done to address these limitations. The emergence of intelligent vehicles [5], [6], [7] promises to radically change this. In our previous work [8] we introduced the concept of a slot-based traffic management system that builds on the idea of intelligent vehicles driving within a virtual slot to increase the traffic efficiency. In this paper, we extend that model to include vehicle-to-vehicle communication (V2V) and apply it to the problem of on-ramp traffic merging, which is known to cause congestion under heavy traffic conditions. The main contribution of this paper lies in the highly efficient nature of the merging algorithm thanks to the cooperation between vehicles on the motorway as well as between vehicles on the motorway and vehicles on the on-ramp. Furthermore, as a side-effect of the efficient and deterministic nature of slot-based driving, congestion can be prevented even under heavy traffic conditions and total journey times can be accurately predicted.

The remainder of this paper is organized as follows: Section II presents the related work; in Section III the slot-based driving model is extended, while in Section IV the on-ramp merging algorithm is described. Section V discusses the evaluation of the algorithm and finally Section VI concludes the paper.

II. RELATED WORK

Motorway on-ramps are critical components of the road network and the way they are designed and operated has a significant impact on the performance of the network. Ramp metering is a widely studied and implemented technique [9] that controls the demand at on-ramps to maintain free flow conditions on the main road thus preventing traffic congestion in the vicinity of the on-ramp. As shown by the fundamental diagram of traffic flow, free flow conditions are determined by a traffic density below the critical density, which in turn is subject to the limitations of human drivers. Ramp metering addresses the consequences of these limitations rather than the limitations themselves.

Past work on automated highway systems (AHS) studied the problem of an automated vehicle merging into a platoon of automated vehicles at an on-ramp [10], [11], [12], [13], [14]. This work focuses on low-level vehicle control issues generally aimed at achieving a safe rather than highly efficient merging.

Davis [15] proposes a cooperative merging strategy where cars on the main road slow down to create a gap into which on-ramp cars can merge. Wang et al. [16] use a slightly different strategy in which vehicles decide in advance on a merging gap between vehicles on the main-road. On-ramp vehicles adjust their speed accordingly before the merging point is reached. Both these approaches assume a one-lane main road and as such cannot take full advantage of the

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cooperation between vehicles on both main road and on-ramp.

Dao et al. [17] consider the problem of increasing traffic efficiency through optimized lane assignment. While this work does not address the on-ramp merging problem, we use a similar concept to intelligently assign lanes to vehicles to increase the number of merging gaps on the first lane of the motorway.

III. COOPERATIVE SLOT-BASED DRIVING

In our previous work we introduced the concept of a slot-based traffic management system (TMS). For the sake of completeness we briefly present the core of the slot model before extending it. The slot-based driving model assumes that all vehicles on the road have identical capabilities and are equipped with radar, DGPS, wireless communication and are (semi)-autonomous. See [8] for a detailed discussion of the assumptions and practical considerations of slot-based driving.

A. Slot model revisited

A slot S is defined as $S = \{z, p, t, b\}$, where z represents the size of the slot, p represents its position (including the lane number) at time t and b the predefined behaviour as a sequence of accelerate, decelerate and lane changing manoeuvres. To drive within a slot, a vehicle needs to be aware of both local information (its own speed, acceleration, positioning and the presence of vehicles ahead) as well as slot information as defined by S. It is the task of the TMS to generate slots at a specific frequency and to provide the slot information to vehicles by means of vehicle-to-infrastructure (V2I) communication. The slot generation frequency determines the headway between slots.

Vehicles are expected to drive normally until the TMS detects that traffic conditions require a more efficient use of the infrastructure. In this case, each individual vehicle performs the vehicle-to-slot (VTS) algorithm in a self-organising fashion. The emergent behaviour of the VTS algorithm is an on-the-fly mapping of vehicles to slots. From that point onwards vehicles are expected to drive within their slots.

We extend the VTS algorithm to accommodate vehicles merging into the motorway at on-ramps. For this purpose, the behaviour b of a slot is limited to a constant speed. As such, slots cannot accelerate, decelerate or change lanes. Instead, it is the vehicles themselves that can change their current slot to a slot located directly ahead on any lane of the motorway.

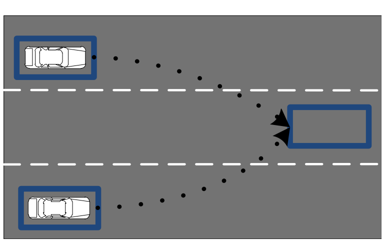


Fig. 1. The slot-changing problem

The slot information provided by the TMS to the vehicles is static: size, initial position and timestamp as well as the planned behaviour do not change over time. However, during the "journey" of a slot along the motorway, the slot's *occupancy status* can vary between *free* and *occupied*. The occupancy status of a slot is required when a vehicle wants to change its slot. This necessitates both knowing that the target slot is not currently occupied by another vehicle as well as knowing that another vehicle is not on its way to moving into that slot, as depicted in Fig. 1. As such, the slot information is extended to $S = \{z, p, t, b, o\}$, where o represents the occupancy status of a slot.

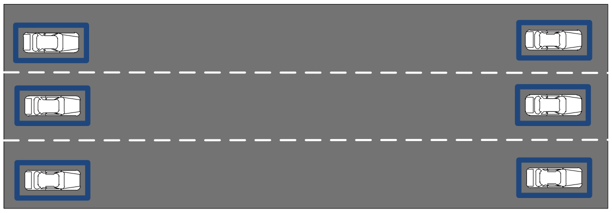
B. Inter-vehicle cooperation

There are two approaches to determining a slot's occupancy status. The first is a *hierarchical approach* where the TMS maintains this information for all the slots on the motorway. Initially, all slots are empty. When a vehicle moves into a slot as a result of the VTS algorithm, it marks the slot as occupied and provides this information to back to the TMS. Note that it is possible for a vehicle to initially move into a slot due to the nature of the VTS algorithm which relies on sensing (e.g. using radar) and does not allow changing slots or lanes in the initial phase. When a vehicle wants to change its slot, it enquires the status of the target slot with the TMS and upon successfully finding an empty target slot it marks the target slot as occupied and the current slot as empty and passes this information back to the TMS. The TMS can then accept this change, in which case the vehicle can proceed with the slot changing manoeuvre, or reject it, in which case the vehicle needs to abort the slot changing manoeuvre. It is necessary to be able to reject changes at the TMS level to address the situation in which two vehicles concurrently attempt to move into the same slot. A simple solution to this problem commonly used by databases is for the TMS to ensure that modifying the old and new slot information takes place in an atomic and synchronized transaction [18]. The hierarchical approach has the advantage of relying solely on V2I, but has the major drawback of scaling poorly with respect to the number of vehicles on the road.

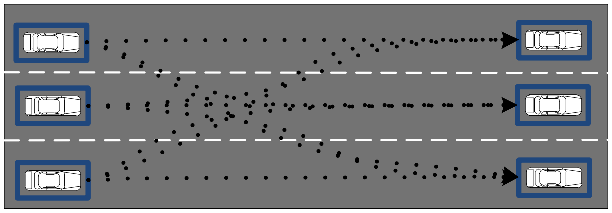
The second is a *distributed approach*. Again, slots are initially empty and vehicles move into them using the VTS algorithm. When a vehicle wants to change its slot, it coordinates this manoeuvre with the neighbouring vehicles by means of V2V to ensure that the target slot is empty and that no other vehicle is aiming for the same slot. This approach is very scalable but requires the implementation of both group communication and a complex coordination protocol. A description of the implementation details of the distributed approach are beyond the scope of this paper. See [19] and [20] for details on vehicular group communication and vehicular coordination respectively.

C. Slot formation

At constant speed and without being allowed to change lanes, the initial position and timestamp of a slot as well



(a)

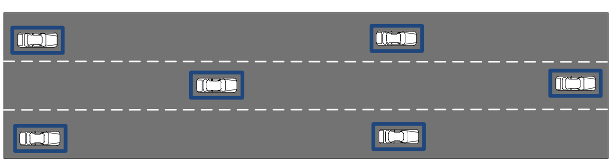


(b)

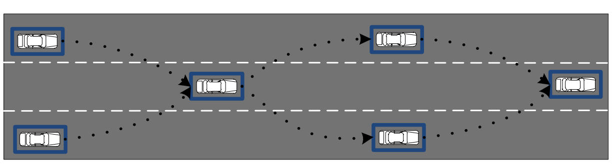
Fig. 2. The parallel formation

as the slot generation frequency determine a specific slot formation across the motorway. If the slots are generated at the same initial timestamp across all lanes, this leads to a formation such as the one shown in Fig. 2(a) . The problem with this formation is that trajectories of parallel vehicles that attempt to move into distinct empty slots ahead intersect. Thus, vehicles need to coordinate in order to avoid collisions, as exemplified in Fig. 2(b).

A better formation is shown in Fig. 3(a). It has the advantage that neighbouring vehicles can move into distinct empty slots ahead in parallel, without needing to coordinate to avoid a collision, as shown in Fig. 3(b). We call this the *chessboard formation* and will be using it throughout the remainder of this paper. To achieve such a formation, slots on even lanes (lanes 2, 4, 6 etc.) need to be generated with half-period offset relative to the slots on even lanes (lanes 1, 3, 5 etc.).



(a)



(b)

Fig. 3. The chessboard formation

IV. ON-RAMP MERGING

Merging on-ramp traffic with the slot-based traffic on the main road requires an extension to the VTS algorithm that performs a mapping of on-ramp vehicles to empty slots on the main road. This is achieved in two phases: slot selection and moving into the slot.

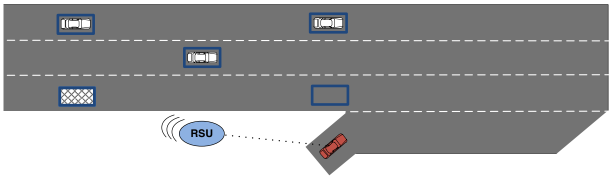
A. Simple merging

In the first phase, a suitable slot needs to be selected. Such a slot must be empty and located on the first lane of the motorway. Furthermore, at the time of selection, the distance between the selection point and the actual point where the roads merge must be large enough to allow the on-ramp vehicle to get into the slot before the actual merging point is reached. We call this distance the *minimum merging distance*.

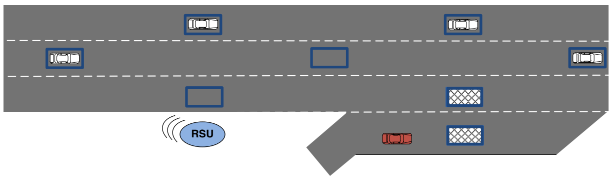
Determining such a slot requires inter-vehicle cooperation. In the previous section, we described two approaches to inter-vehicle communication: distributed and hierarchical. For the on-ramp merging scenario, to accommodate the minimum merging distance, the distributed approach requires coordination between many vehicles over a large area. Furthermore, the coordination takes place between vehicles located both on the main road and on ramp, so that the communication area might contain objects that interfere with the wireless communication. These factors and the limitations of V2V communication render make the distributed approach very hard to implement in practice. The hierarchical approach on the other hand does not suffer from these problems but still faces the problem of scaling badly with respect to the number of vehicles.

We propose a hybrid approach the combines the best aspects of the hierarchical and distributed approaches. The cars on the main road use the distributed approach to coordinate. A road side unit (RSU) is located at the slot selection point and acts as a proxy between the vehicles on the main road and the on-ramp vehicles. The RSU is able to sense the location of vehicles on the main road and is able to coordinate with them using V2V communication to determine suitable slots. When such slots are found the RSU marks them as occupied for on-road vehicles, effectively blocking any attempt of any vehicle on the main road to move into that slot. On-ramp vehicles communicate with the RSU using V2I communication and request a slot. Once such a slot becomes available, the RSU communicates the slot information to the vehicle. This approach scales well with respect to the number of vehicles in the network and does not suffer from the same problems as the distributed approach due to its employment of V2I communication between the RSU and on-ramp vehicles.

After the on-ramp vehicle has received a suitable slot, the moving into the slot phase commences. For this purpose, the vehicle creates a virtually identical slot clone, the only difference being that the cloned slot is located on the on-ramp rather than on the main road. The vehicle then uses the VTS algorithm as described in [8] to move into the cloned slot before the merging point is reached. Right before the merging point, the original and cloned slot are in perfect alignment and the vehicle performs a lane change towards the first lane of the main road and changes its target slot to the original slot, moves into this slot and finishes the merging procedure. This process is described in Fig. 4.



(a)



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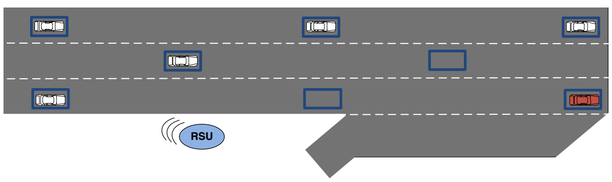

(c)

Fig. 4. On-ramp merging

B. Optimisation

The now extended VTS algorithm merges on-ramp vehicles into free slots on the first lane of the motorway. As such, the VTS algorithm does not take advantage of free slots on the other lanes of the motorway. This can be achieved with a basic optimisation, based on the previously described ability of vehicles to change slots. Before the merging, vehicles driving in slots target free slots to the left front of the current slot, as shown in Fig. 5. The result of this optimisation is an increase in the number of free slots on the first lane which enables a higher throughput of vehicles on the on-ramp. For simplicity, destination off-ramps are not considered in this paper. The extended and optimised VTS algorithm is shown in Algorithm 1. See [8] for a detailed description of the VTS mapping phase.

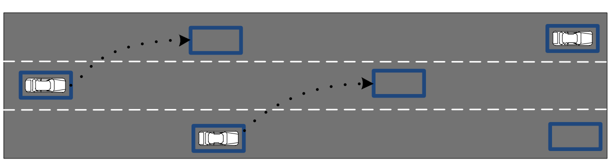

Fig. 5. Moving to free slots to the left-front of the current slot

V. EVALUATION

The on-ramp merging algorithm extends our slot-based TMS implemented on top of the VISSIM traffic simulator [21]. VISSIM's external driver model DLL is used to replace VISSIM's emulation of human driving with our slot-based driving model. The time-step fashion in which VISSIM operates means that the external driver model is called at each time-step for each vehicle in the network. Information

```
begin VTS
    Vehicle receives slot information and the start point and end
    point of the VTS mapping phase;
    if on main road then
        if does not have slot then
            begin Initial mapping to slot
                if can sense another Vehicle ahead then
                    while can get into the next free slot before
                    the end point of VTS do
                        get at exactly 1 inter-slot headway
                        behind Vehicle in front;
                    end
                    if the distance to the Vehicle ahead is more
                    than 1 inter-slot headway then
                        get into the first slot ahead;
                    end
                end
                else
                    while cannot sense a Vehicle ahead and can
                    get into the next free slot within the border of
                    VTS mapping phase do
                        accelerate to maximum speed and
                        maintain this speed;
                    end
                    if can sense another Vehicle ahead then
                        while can get into the next free slot
                        within the border of VTS mapping phase
                        do
                            get at exactly 1 inter-slot headway
                            behind Vehicle in front ;
                        end
                        if the distance to the Vehicle ahead is
                        more than 1 inter-slot headway then
                            get into the first slot ahead;
                        end
                    end
                    else
                        get into the first slot ahead;
                    end
                end
            end
        end
        else
            if Free slot towards the left front then
                move into the free left front slot;
            end
            else
                maintain current slot;
            end
        end
    end
    else
        get free slot from RSU;
        move into free slot;
    end
end
```

Algorithm 1: VTS algorithm

about the vehicle's current speed, lane, acceleration and steering, as well information about neighbouring vehicles is provided by VISSIM as an input to the external driver model. The external driver model is then expected to process this information and return the desired speed and steering of the respective vehicle. This is used by our implementation to perform the vehicle control required to get into and drive within a slot, based on the assumption that all vehicles are capable of driving (semi)-autonomously as discussed in [8].

The hierarchical approach based on V2I was used to implement the inter-vehicle cooperation, due to its simple implementation within the simulation environment. A so-called

Slot Provider is responsible for generating and maintaining a list of slots. The slots are generated at a frequency of 1s and are set to have a constant speed of 30 m/s. Slots on odd lanes are generated 0.5s before their counterparts on even lanes. The Slot Provider provides the slot information to the vehicles and marks slots as free or occupied when vehicle moves out respectively into slots. For the on-ramp merging scenario, the Slot Provider performs the task of the RSU and assigns free slots on the first lane to on-ramp vehicles. Note that in practice, for reasons advocated in the previous section, a hybrid rather than hierarchical approach based on both V2I and V2V would be more appropriate. However, within the simulation, the hierarchical approach based on V2I is sufficient.

The road model used to evaluate the merging consists of a 3-lane motorway and an on-ramp. The main road segment has a total length of 3000m. The first part of this segment is used by the VTS algorithm to get vehicles driving within slots. The second part is used by the vehicles to move into free slots located to the left front of the current slot when inter-vehicle cooperation is employed. At 2600m, the main road merges with the on-ramp. The length of the on-ramp's acceleration lane is 180 meters, which is the default value suggested by the Highway Capacity Manual [22]. The RSU is located at a minimum merging distance of 230m, computed as the length of the acceleration lane (180m) plus an extra 50m to ensure that on-ramp vehicles have enough time to get to the speed of the slot.

The slot-based merging algorithm is evaluated with and without the optimisation described in the previous section and compared against a simulation of human drivers as performed by VISSIM's Wiedemann '99 model [23]. The efficiency of the merging is evaluated with respect to:

- **Throughput** : the maximum number of vehicles that can merge from the on-ramp into the main road within an hour
- **Delay** : the average delay experienced by vehicles on the on-ramp calculated as the difference between the average travel time and the ideal travel time (no other vehicles in the network)

under:

- **Medium traffic conditions** : main road flow of 3600 vehicles/hour
- **Heavy traffic conditions** : main road flow of 4700 vehicles/hour

A. Throughput

The throughput on the on-ramp was evaluated for human drivers (manual) and slot-based driving with and without the optimisation provided by the cooperation of vehicles on the main road. Each of the three was evaluated under medium and heavy traffic conditions. The results of this evaluation are shown in Fig. 6. Under medium traffic conditions, the slot-based driving without cooperation achieves a 41% increase in throughput when compared to human drivers. Slot-based driving with cooperation performs better and achieves a 106% increase in throughput compared to human drivers. The two algorithms perform even better under heavy traffic conditions compared to human drivers: 230% and 452% increase for slot-based driving without and with cooperation respectively.

These results show that the throughputs achieved by both slot-based driving algorithms clearly outperform the throughput of the merging performed by VISSIM's emulation of the human drivers. As expected, cooperation between vehicles on the main road has a positive effect and increases the throughput on the on-ramp. Furthermore, the slot-based driving algorithms perform even better under heavy traffic conditions when compared to human drivers. It is worth noting that heavy traffic causes a decrease of on-ramp throughput across all three merging approaches when compared to medium traffic. However, for human drivers the throughput under heavy traffic decreases by 64% when compared against medium traffic, compared to 17% and 4% for slot-based driving without respectively with cooperation.

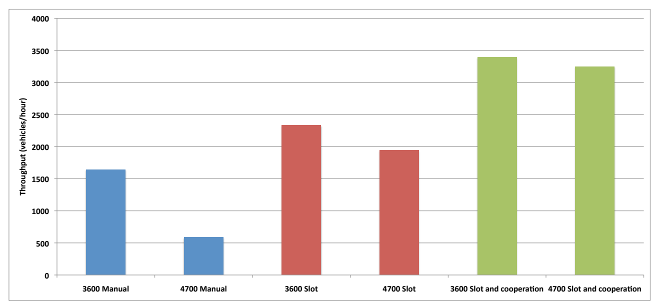

Fig. 6. Maximum on-ramp throughput

B. Delay

The on-ramp delay was evaluated also under medium and heavy traffic conditions on the main road. Fig. 7 and Fig. 8 show the delay of human drivers, slot-based driving and slot-based driving with cooperation under medium and heavy traffic conditions respectively. The on-ramp traffic flow was gradually increased from 200 vehicles/hour to 2000 vehicles/hour which corresponds to very heavy on-ramp traffic conditions. We can observe that, for manual drivers, the delay increases exponentially with respect to the on-ramp flow. For the two slot-based driving algorithms the delay remains small and increases slightly as the on-ramp flow increases. The traffic on the main road increases the delay for human drivers but has very little effect on the other two approaches, thanks to the high throughput and efficient merging of the slot-based approach.

Note that that in Fig. 8 the measured delay for 500 vehicles/hour is smaller than the delay obtained for 400 vehicles/hour. This result shows that there are other factors that can influence the manual merging procedure such as the distribution of vehicles across both main road and on-ramp. For example, a platoon of vehicles on the main road reaching the merging point at the same time as a platoon of vehicles on the on-ramp can have a significant impact on the merging. This is not a problem for slot-based driving since the VTS algorithm was designed to break-up such platoons when vehicles are mapped to slots, as it can be observer from Algorithm 1.

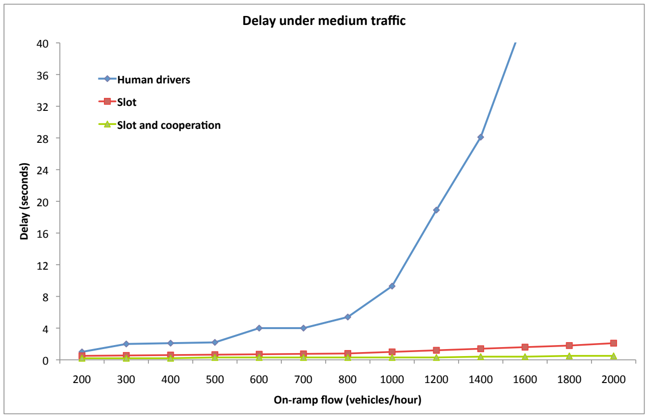

Fig. 7. On-ramp delay under medium traffic conditions on the mainroad

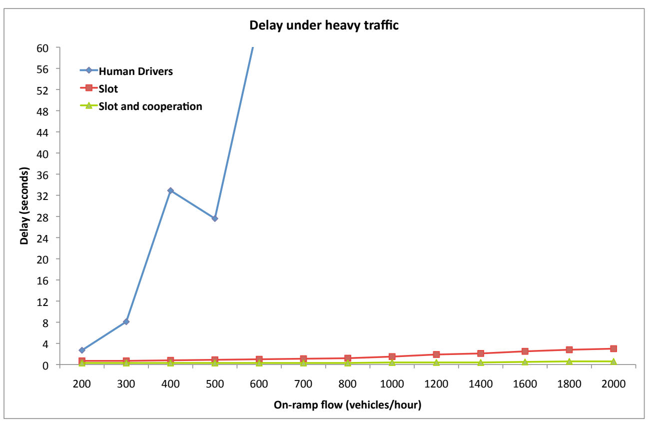

Fig. 8. On-ramp delay under heavy traffic conditions on the main road

C. Discussion of the results

These results show that slot-based approach to on-ramp merging performs a very efficient merging, clearly out-performing the human drivers as simulated by VISSIM. However, traffic simulators such as VISSIM are known to inaccurately simulate the merging performed by human drivers [24]. In VISSIM's case, this is caused by the fact that on-ramp vehicles patiently wait for an empty gap on the main road, potentially causing a large queue to be formed on the on-ramp [25]. As such, it does not account for aggressive merging from the on-ramp or for the cooperation of drivers on the main road slowing down or changing lanes right before the merging point to accommodate on-ramp vehicles. In our experiments we observed that for manual driving under high traffic demand on both main road and on-ramp, the free-flow state of the main road is maintained despite a large queue being formed on the on-ramp. In real-world conditions, on a highway without ramp metering, aggressive merging and main road vehicles slowing down could reduce the length of the on-ramp queue. However, this often leads to congestion on the main road, which in turn can have a negative effect on the on-ramp throughput and delay on both main road and on-ramp. It is therefore hard to precisely determine how the inaccurate VISSIM simulation affects the throughput and delay results obtained in the evaluation of merging performed by human drivers.

Nevertheless, the results of the slot-based driving algorithms do not rely on the human driver model provided by VISSIM and therefore do not lack in accuracy. The very high efficiency of this approach is demonstrated by the throughput achieved by the cooperative slot-based merging which approaches the theoretical limit of 3600 vehicles/hour for slots generated at a frequency of 1s.

VI. Conclusion and Future Work

This paper presents an algorithm for efficient merging of traffic on the main motorway with traffic joining the motorway at on-ramps. The algorithm is based on our previous work on slot-based driving which uses the concept of a slot as an abstraction layer between infrastructure operators aiming to increase the efficiency of traffic and car manufacturers aiming to make driving easier, safer and more efficient. As such, infrastructure operators can focus on designing slot-based techniques to prevent congestion and increase the reliability of traffic while car manufacturers can focus on enabling emerging intelligent vehicles to drive in a slot.

The main contribution of the slot-based merging algorithm lies in the cooperative approach used by vehicles across both the main road and on-ramp. The results of our evaluation clearly confirm our assumption that this leads to a highly efficient merging. Due to the limitations of VISSIM, in the future we plan to use real data from an on-ramp to compare against our slot-based merging.

In the road model used in this paper off-ramps were not considered. This can have an impact on the cooperation of vehicles on the main road since vehicles that plan to exit the network at an off-ramp closely following an on-ramp cannot leave the first lane even if there are free slots to the left front of the current slot. We plan to extend our model with off-ramps and weaving sections as well as increase the number of on-ramps and subsequently improve our optimisation strategy to account for these factors. Future work will also address fault tolerance issues such as malfunctioning vehicles or a breakdown in communication and their impact on both safety and efficiency.

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