Vision of Congestion-Free Road Traffic and Cooperating Objects

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November 2005

Overview. This is a vision of cooperating vehicles that help keep roads free of traffic congestion. This vision explores the concept of dynamic time-space corridor that can be negotiated between cooperating vehicles to guarantee congestion-free journeys from departure to arrival.

I. Vision

This vision of the future is motivated by the increasing traffic congestion around our densely populated metropolitan areas. There is no need here to reference the numerous studies on traffic safety and pollution carried out by governmental agencies over the years or to bring forward accident, carbon dioxide, and driver-stress figures. Everyone that has been in a large city in rush hour has most likely experienced how stressful it is to be locked in traffic, noticed the pollution in the air, considered how they could have been injured on the road, and wondered how much better their lives would be without traffic congestion.

Typical science fiction solutions to this problem of traffic congestion first come to mind, including for example the teleportation devices in Asimov's It's Such a Beautiful Day story or the ability to travel between alternate history Earths in Asimov's Living Space story. However, here we are not restrained only by our imagination but want to consider traffic congestion solutions that can plausibly be built within the next ten years. As such, we assume the following:

- In ten years, vehicles will be able to communicate, to sense their environment, to control their speed and direction, and in general to cooperate with each other.
- In ten years, numerous objects on the urban landscape will similarly be able to communicate and sense their environment – we are thinking for example of communicating and sensing signposts, sidewalks, and street lamps.

These seem reasonable assumptions. Manufacturers are already enhancing cars with sensors that help drivers to park and providing GPS compasses as standard equipment on luxury cars. Reasonably, full integration of on-board, software- and hardware-improved computers with wireless communications and environmental sensors is within ten years' reach. Furthermore, trials of numerous networked and sensing objects have been conducted in urban areas. This is a first step towards the full deployment of such objects throughout cities and metropolitan areas.

Our vision is that traffic congestion can be prevented with the help of these cooperating vehicles and urban landscape objects. In particular, we see these cooperating objects helping people drive more intelligently – or rather more cooperatively – with the aim of preventing congestion. Some laboratory prototype vehicles may today already detect the proximity of other vehicles or obstacles and automatically break to prevent collisions, or detect traffic congestion ahead and suggest alternate routes to drivers. Our vision is that of a solution that is beyond what these prototype vehicles can do to alleviate traffic congestion. In particular, with the help of cooperating objects we expect to prevent congestion before it occurs, self-regulating traffic such that e.g. avoiding collisions and finding alternate congestion-free routes may no longer be necessary to prevent congestion. In our vision, cooperating vehicles help to self-regulate traffic by negotiating in advance a clear corridor in space and time that goes through the roads of their intended journey. Such a corridor is much like a Time-Division Multiple-Access (TDMA) data slot that propagates through a communications channel. A vehicle that obtains access to such a time-space corridor will not experience congestion as other vehicles will manoeuvre to keep such a corridor unobstructed. In our vision, all the vehicles in what otherwise would have been a traffic jam have their own time-space corridors and, as such, move without causing or experiencing congestion. This is the core of our vision of congestion-free road traffic.

The following sections describe in more detail the system that we have envisioned to support congestion-free road traffic using cooperating vehicles and urban landscape objects.

II. Envisioned Supporting System

Time-space corridor. The major concept of our vision is the time-space road corridor that we also term virtual vehicle slot. Virtual vehicle slots propagate through a lane of the road at the recommend speed of that lane (see fig. 1). Once a virtual slot is assigned to a vehicle it cannot be overrun by other vehicles. On one hand, vehicles moving in their virtual slots will not overrun the virtual slots of other vehicles as 1) the speed of virtual slots on the same lane is the same; and 2) virtual slots are wide enough to guarantee a minimum safety distance between vehicles of consecutive slots. On the other hand, vehicles that have not been assigned a virtual slot will have to avoid overrunning virtual slots by e.g. changing lane or increasing their speed. As such, a vehicle to which a virtual slot is assigned is guaranteed to arrive at its destination without experiencing traffic congestion. For example, we expect lane junction congestion to be prevented as virtual slots from incoming lanes are synchronised and propagate to the outgoing lane at the lane's recommended speed. Similarly, we expect that virtual slots will allow vehicles to maintain their speed and as such help prevent e.g. wave phenomena typical in traffic congestion in which vehicles periodically accelerate and then almost immediately have to break.

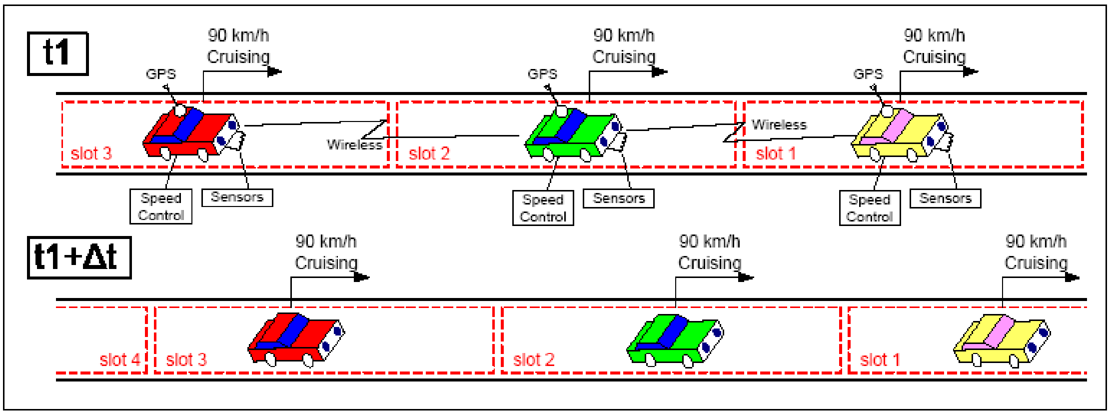

Figure 1 – Example of a single lane with moving virtual vehicle slots. Notice how each slot moves forward with time at the recommended speed of the lane (90 km/h). Notice also that the vehicles communicate with each other, determine their position, sense their environment (e.g. proximity detection), and control their speed in order to keep to their moving virtual slots. (Note: *Cruising* vehicles have zero acceleration.)

Cooperating Vehicles. In our vision, cooperating vehicles that can sense their environment will be able to implement this virtual slot system. These vehicles will be able to determine their position, speed, and direction and then successfully negotiate access to a virtual slot. Once a slot is assigned to the vehicle, the vehicle must not stray from the slot and thus speed and direction must be controlled. We don't expect vehicles to be able to fully and automatically 'drive' themselves in ten years – this will likely take longer to achieve. However, in ten years we expect vehicles to be able to suggest appropriate action to drivers such as reducing or increasing speed. For example, in lane junctions, two vehicles driving on different lanes will detect that their virtual slots will collide once their lanes have merged. The vehicles will negotiate their new slots on the outgoing lane (e.g. slightly offsetting the slots in opposite directions so they don't overlap) and inform their drivers that they should accelerate or break just enough to keep to the new slots.

Figure 2 illustrates this example. At time t_1 the vehicle on the right lane (slot 2) needs to change lane. This vehicle would have a number of approaches to do so. 1) This vehicle breaks and waits for an opening on the left lane. The vehicle in slot 3 would not be affected, but this would cause the vehicle in slot 2 to be left behind its slot, to run into new slots that would potentially appear behind it, and to cause traffic congestion. 2) This vehicle keeps its speed and changes to the left lane, not keeping the safety distance to the vehicle in slot 3 behind it (fig. 2, option *a*, time $t_1 + \Delta t$). This would likely cause the vehicle in slot 3 to do an emergency break, potentially running into slot 4 and starting wave congestion. 3) This vehicle communicates with the vehicle in slot 3 to attempt to coordinate the lane change (fig. 2, option *b*, time $t_1 + \Delta t$). As a result, the vehicle in slot 3 would slightly delay its slot (breaking) and the vehicle in slot 2 would slightly advance its slot (accelerating) so that upon lane change the safety distance is maintained and the vehicles can keep to their new, offset slots. Note that offsetting these slots requires more than the coordination between vehicles in slots 2 and 3. In fact, the vehicle in slot 3 must coordinate with the vehicle in slot 4 so that slot 3 does not run into slot 4 as it temporarily lags behind. This approach would effectively prevent congestion as vehicles cooperate to keep to their slots.

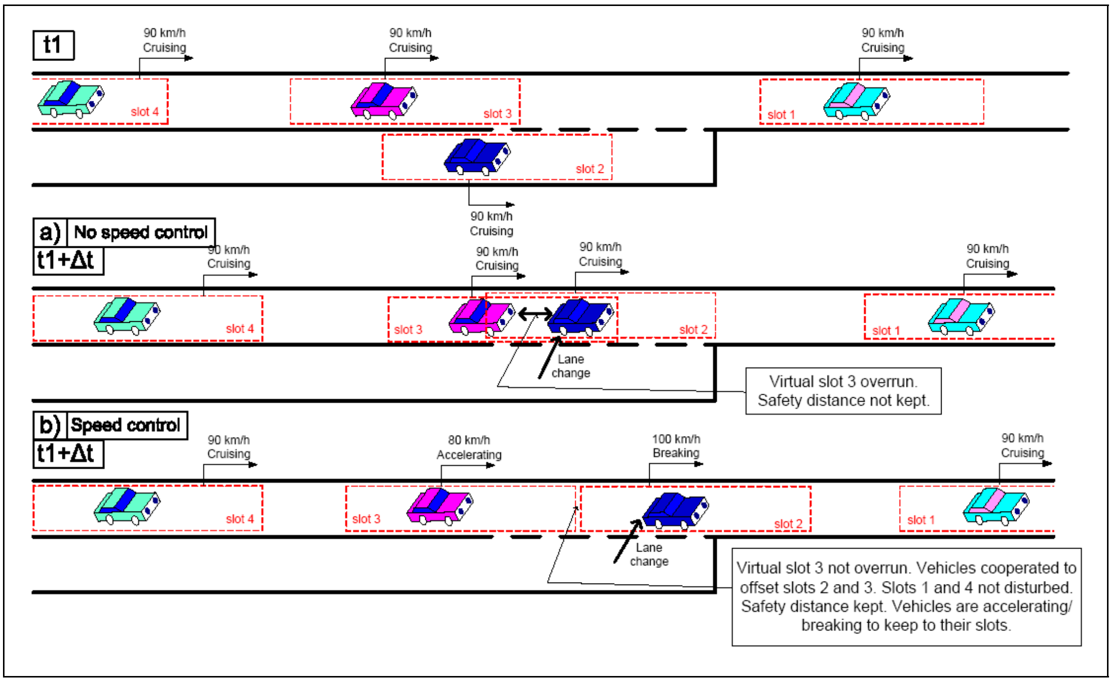

Figure 2 – Example of merging lanes a) without and b) with vehicle cooperation.

Self-regulating flow control. In addition to controlling the speed and safety distance between vehicles using the virtual slot system, we must limit the rate of vehicles that enter a lane and make sure that the rate of vehicles that exits the lane is not inferior to the rate of entry. We envision a mechanism to control the inbound and outbound vehicle flows of a lane and prevent traffic congestion. This mechanism is two-fold.

Firstly, our cooperating vehicles must allocate a virtual slot in a lane before they enter that lane. Failure to allocate such a slot, namely in the case where the lane has reached the maximum inbound vehicle flow, will result in the vehicle not being allowed to enter the lane. Thus vehicles self-regulate the inbound flow of a lane by abstaining from entering the lane at peak conditions. Notice that virtual slot speed and length determine the maximum virtual slot rate. If the inbound traffic flow exceeds the maximum slot rate then the distance between vehicles diminishes. This forces drivers to maintain safety distances by reducing speed and, as such, causes congestion. In order to prevent such congestion, slot allocation fails in our envisioned system when inbound traffic flow is larger than maximum slot rate.

Secondly, outbound flow must not be inferior to inbound flow if congestion is to be avoided. We try to better understand outbound flow by considering what happens to vehicles when they leave a lane. Outbound vehicles will either enter another lane or stop at a parking space. Eventually however, every vehicle will finish its journey at a parking space. Difficulty in finding parking space will diminish the outbound flow of parking vehicles and potentially lead to congestion. In our vision, the urban landscape is full of different sensing and cooperating objects. In particular, drivers will rely on these objects to find available parking space. These objects can be, for example, wireless sensor networks deployed on sidewalks and that can detect the presence of vehicles on nearby parking spaces. Moreover, these objects can cooperate with vehicles that need to park by making parking space reservations and preventing other vehicles to park in places that have already been reserved. For an end-to-end approach to traffic congestion, vehicles have to allocate their destination parking space before they start their journeys – thus self-regulating outbound as well as inbound flows.

III. Supporting Simulations

We have used a third-party open source road traffic simulator to test the concepts of our vision, namely the virtual vehicle slot. The third-party simulator source code and papers on traffic simulation in general and on wave phenomena in particular can be found at http://www.helbing.org/. Figure 3 shows congestion on a typical lane junction. Notice how vehicles have to stop and queue to change to the main lane. When a vehicle with a slow speed changes to the main lane, it will cause the vehicles behind it on the main lane to reduce their speed to prevent them from colliding with the slow vehicle ahead of them. This causes congestion and in particular the wave phenomenon that can be noticed on the curve of the main lane. Compare this with fig. 4 in which vehicles coordinate lane change with the vehicles on the main road. Notice in particular that 1) the inbound flow on both lanes and the simulation time are the same as those on fig. 3 and that 2) no wave phenomenon or congestion in general occurs in fig. 4 as vehicles coordinate lane change with the vehicles on the main lane.

IV. Related Work

Our review of related work on using cooperating vehicles for preventing traffic congestion identified two separate research efforts.

Firstly, we have identified research whose main focus is on road traffic per se. For example, the U.S. Intelligent Transportation Systems (ITS) program [1] has proposed new initiatives such as integrated corridor management systems, cooperative intersection avoidance systems, and vehicle infrastructure integration. Another example is the Japanese ITS program that focuses e.g. on vehicle information and communication systems (VICS) [2] and on advanced cruise-assist highway systems (AHR) [3]. These programs build on road network planning, on vehicle sensing, and on vehicle-to-road communication to prevent congestion and avoid collisions. Cooperation between vehicles is only used to support collision avoidance and not to prevent congestion as in our envisioned solution.

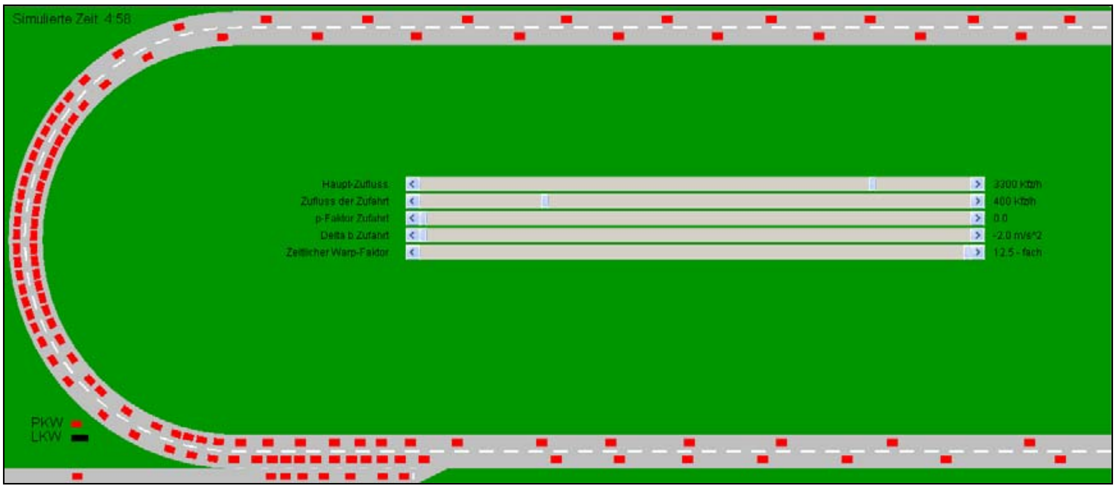
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Figure 3 – Typical scenario provided in the original simulator source code. (Notice the congestion.)

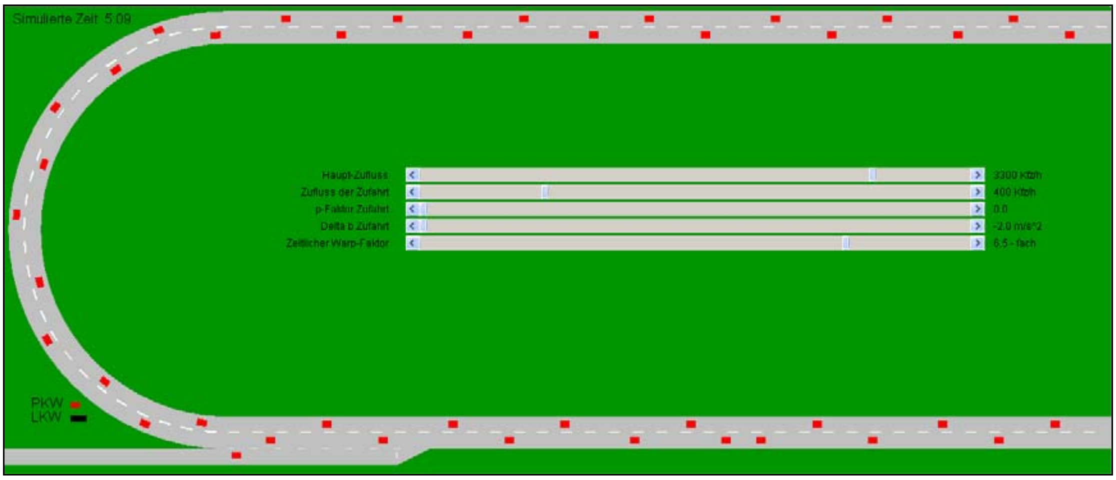
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Figure 4 – Exactly the same scenario as in fig. 3 except that the simulator was modified to support vehicles coordinating lane change with the vehicles on the main lane. (Notice the absence of congestion.)

Secondly, we have identified research whose main focus is on communications, sensing, and software for cooperating vehicles. For example, research at Lancaster University [4] has yielded an autonomous vehicle capable of cooperative behaviour without human control and of autonomous navigation. Another example is the ITS work by NEC [5] that focuses on e.g.

congestion monitoring using sensor information from vehicles (termed Probe Information System) and vehicle-to-vehicle communication for transmitting traffic congestion events. Although these contributions build on the technology for cooperating vehicles, they are not intended to prevent congestion in advance (i.e. before congestion occurs) as our envisioned solution is.

In conclusion, although research on intelligent transportation systems has focused e.g. on traffic network planning, on automated vehicle collision avoidance based on proximity sensors and vehicle cooperation, on traffic network congestion monitoring, on vehicle-to-vehicle wireless communication, and on autonomous vehicle navigation, to our knowledge there is no related work or publicly available vision on vehicle cooperation for preventing traffic congestion and in particular on preventing such congestion with the help of dynamic time-space corridors.

V. Summary

We have described our vision of congestion-free road traffic using cooperating objects. In particular, cooperating vehicles are able to negotiate virtual vehicle slots needed for the whole of their passengers' journey, i.e. from departure to arrival. These slots have guaranteed speed and safety distances to other slots and as such will not be overrun by other vehicles. Vehicles in these slots will not experience traffic congestion. Our vision includes the negotiation of the virtual slots at the consecutive lanes through which the vehicle needs to circulate and of parking space for the end of its journey. Cooperating vehicle and urban landscape objects provide support for such negotiation and thus enable our vision of congestion-free road traffic.

To the best of our knowledge, the concept of time-space corridors for vehicles is original. This concept was inspired by research on data communications protocols. Furthermore, we have described an innovative use of cooperating and sensing vehicles as we expect these to negotiate and establish congestion-free virtual slots. We expect that the implementation of this congestion-avoiding system will bring forward new challenges and technical progress. We also expect the social, economical, and environmental impact of deploying our envisioned system to be tremendous. Environmentally, we expect that without traffic congestion there will be less pollution on the roads. Economically and socially, we expect that people will spend less time commuting and in general be less stressed and more productive. Finally, we expect the deployment of our envisioned system to become a source of technical and economical development for the vehicle and telecom industry.

References

[1] US ITS New Initiatives' web site. http://www.its.dot.gov/newinit_index.htm

[2] Japanese ITS VICS web site. http://www.its.go.jp/etcvics/vics/index_e.html

[3] Japanese ITS AHR web site. http://www.ahsra.or.jp/index_e.html

[4] Thirunavukkarasu Sivaharan, Gordon Blair, Adrian Friday, Maomao Wu, Hector Duran-Limon, Paul Okanda, and Carl-Fredrik Sørensen. *Cooperating Sentient Vehicles for Next Generation Automobiles*. Proceedings of the 1st International Workshop on Applications of Mobile Embedded Systems, Boston, June 2004.

[5] Makoto Maekawa. *ITS (Intelligent Transportation Systems) Solutions.* NEC J. of Adv. Tech., Special Issue on Advanced Technologies and Solutions toward Ubiquitous Network Society. Summer 2004.