A study of collaborative influence mechanisms for highway convoy driving

Majid Ali Khan, Damla Turgut and Ladislau Bölöni
School of Electrical Engineering and Computer Science
University of Central Florida
Orlando, FL 32816–2450
Email: khan@bond.cs.ucf.edu,turgut@eecs.ucf.edu,lboloni@eecs.ucf.edu

ABSTRACT

Convoy driving on highways is a desirable behavior which reduces the risk of highway accidents and makes traffic faster and more fluent. Recent technologies, such as intelligent cruise control devices explicitly facilitate convoy driving by providing a fully automated means for following the previous vehicle. Participating in a convoy, however, requires compromises from the vehicles, such as slowing down to the speed of the lead vehicle; thus many drivers choose not to join any convoy. Collaborative convoy driving systems, based on vehicle-to-vehicle communication, promise to deliver means for the vehicles to influence the speed of the convoy, thus improving its utility. We discuss the mechanisms of convoy participation, including the decision to join and leave the convoy, and the mechanisms through which the vehicles can influence the convoy speed. In an experimental study, we compare three influence mechanisms: the "adapt speed to the leader" mechanism used by human drivers and intelligent cruise control systems and two collaborative influence mechanisms which require vehicle to vehicle communication. We show that the collaborative cruise control methods deliver better macroscopic performance measures: more vehicles participating in convoys, higher average speed and lower number of overtakings.

1. INTRODUCTION

The desired speed of a driver on a highway depends on the capabilities of the vehicle, the driver's driving skills, style, current goal and state of mind, as well his or her assessment of the likelihood of a fine if the vehicles exceeds the posted speed limits. If the vehicles on a highway have a wide spread of desired speed, it leads to a behavior with many lane changes, overtaking, accelerations and decelerations. In practical traffic, it increases the likelihood of accidents, and slows down the traffic by creating bottlenecks.

The ideal traffic behavior would be for all vehicles to travel at the posted speed limit, and to maintain this speed constant, for instance, through the use of a cruise control system. It is also desirable that vehicles position themselves at uniform distance from each other, that is, they form *convoys*. Unfortunately, cruise control systems have slight variations, which make vehicles "creep" closer to each other. In these occasions the drivers need to take control and either take over the vehicle in front or adjust the speed lower. The latter might lead to a chain reaction, where the following vehicles need to make similar decisions. This effectively means that the vehicles have the choice to either (a) adjust to the speed of the slowest vehicle in the convoy or (b) leave the convoy and engage in a series of overtakings.

Many recent vehicles are equipped with an "intelligent cruise control system", which measures the distance from the vehicle in front using a laser or radar and adjusts the speed accordingly. This makes the job of the driver easier, as it automatically performs the slow-down operation, and, in the limits of the previously set preferred speed, it can also perform acceleration. However, the problem still remains that the vehicles will adopt the speed of slowest member of the convoy.

One way to improve this architecture is to create a convoy where the vehicles communicate with each other. Note that communication alone does not change the picture, unless vehicles, in some respect, are responsive to the "common good". For instance, if a convoy of 10 vehicles has a first vehicle whose desired speed is 2mph lower than the followers, the followers might "convince" the leader to increase the speed, rather than performing a series of traffic-disruptive overtakings. In traditional traffic, follower vehicles sometimes pressure the first vehicle by driving closer than the comfort distance of the driver. In general, a driver might choose to collaborate with the convoy as long as the departure from the preferred speed is not too large, as the driver himself benefits from the smoother traffic. In is beyond the scope of this paper to discuss the mechanisms through which the interests of the individual vehicles, the convoy and the general public are reconciled[1].

While the formation of convoys is sometimes an explicitly planned operation, most often it is happening in an ad hoc manner between vehicles whose drivers do not know each other, might not have common goals and can communicate only through indirect means. Convoys are formed and terminated dynamically; their life cycle ranges from tens of seconds to several hours. Vehicles can join and leave, and convoys themselves can split and merge. If we consider the vehicles to be intelligent agents, highway convoy driving is a microcosm of problems including communication (both at networking and semantic level), team formation, leader election, negotiation and planning.

In previous work [6] we have proposed an architecture which managed the formation, creation and splitting of convoys through vehicle to vehicle communication. As a note, our hardware implementation was based on Crossbow MICA2 motes communicat-

[1]One way to assure this is through legislation. Considering the safety advantages of convoy driving, it is possible to allow a higher speed limit for convoys: eg. "speed limit 70mph, up to 80mph when in convoy".

ing on the 868/916MHz range. Current efforts around the Dedicated Short Range Communications (DSRC) project and the IEEE 802.11p standardization effort makes it likely that future vehicle-to-vehicle communications will happen in the 5.9 GHz band.

The determining feature of the convoy formation is the *influence mechanism*, the way in which the vehicles influence each other's speed. As we had seen, in convoy driving without inter-vehicle communication the only influence mechanisms possible are the adaptation to the speed of the vehicle in front (with or without explicit adaptations to maintain a following distance). If we assume the existence of inter-vehicle communication, other adaptations are possible. Examples are increasing the speed at the request of the vehicle in the back, decreasing the speed at the request of the vehicle in the back, increasing the speed at the request of the vehicle in the front, and so on.

In [6] we have described an influence mechanism which relies on the Social Potential Fields (SPF) model [9] proposed in the field of mobile robots.

In addition to the influence mechanism, the traffic behavior is also affected by the *convoy participation policy* of the vehicle. This policy governs the choice of the vehicles whether to join the convoy (and, implicitly, to obey the influence mechanism) or to leave the current convoy and either drive alone or join another convoy. For the purpose of this paper we will assume a very simple policy based on *threshold with friction* where the desirability of the convoy is determined by the difference in the speed of the convoy and the desired speed of the vehicle. This policy also adds a cost for the joining and leaving a convoy to prevent frequent defections.

Our experiments with this architecture in [6] have concentrated on the local behavior of several vehicles. As intelligent cruise controls are deployed in more and more vehicles and the possibility of wide scale deployment of collaborative cruise control draws near through the standardization of the vehicle-to-vehicle communication protocols, we are interested in investigating how the deployment of such systems affect the general traffic. We are mainly interested in integrative measures such as the mean velocity of vehicles, the number, size and size distribution of convoys and the number of vehicle overtakings.

The remainder of this paper is organized as follows. We survey related work in Section 2. The convoy formation mechanism and influence mechanisms considered are described in Section 3. We then use these mechanisms in a simulation study involving a large number of vehicles, study the emergent traffic behavior and measure the integrative properties in Section 4. We conclude in Section 5.

2. RELATED WORK

The study of vehicular traffic has attracted the interest of researchers for several decades. One of the schools of thought treats traffic in analogy to various physical phenomena. A thorough overview of proposed models is provided by Chowdhury et al. [3]. One approach is to treat traffic flow in analogy with the hydrodynamic theory of fluids [1]. In this case traffic is seen as a one dimensional compressible fluid; the characteristics of the individual vehicles are not considered, only their density on the road. An alternative approach is the kinetic theory, where traffic is treated as a gas of interacting particles, with each particle representing a vehicle. As molecules in the gas have random movements described by the Boltzmann equation, on its own, this model can not describe the purposeful movements of vehicles. One approach is the Paveri-Fontana model [8] which assumes that each vehicle, in contrast to molecules in the gas, has a desired velocity towards which the actual velocity converges in the absence of other vehicles.

Of a particular relevance to our to our approach are the "car-following theories" of the traffic flow. In these models the traffic is seen as a set of objects interacting under a set of forces analogous to the Newtonian mechanics. Various proposed models make the force acting on the vehicle dependent either on the parameters of the preceding vehicle, or several of the preceding vehicles. Note that the different influence mechanisms in convoy formation (to be discussed later in this paper) can be seen as specific instances of these classes of models.

Another influential approach of traffic modeling uses the language of cellular automata, a representative example being the Nagel-Schreckenberg model [10].

What can the agent community bring to this respected body of research? First of all, the concept that the drivers on the highway are humans with autonomous decision making capabilities. While humans might drive long stretches of road in ways predictable from their environmental conditions, they also frequently exercise their decision making capacity in joining a convoy, accelerating to catch a green light, overtaking to escape an erratic driver and so on. The vehicle-to-vehicle communication systems currently in development will likely change the driving dynamics and their effects needs to be modeled by treating the vehicles as agents.

Although the technical means of implementing vehicle-to-vehicle communication are only beginning to become available, there is already a significant literature in the using agents in the control and modeling of vehicles. Dresner and Stone [4] propose an intersection control mechanism where agent-based reservations replace the traffic lights. They prove the superiority of the approach through simulation and show that the reservation method closely approximates an overpass (which is the optimal, although costly solution for intersection management).

Laumonier et al. [7] work towards a cooperative adaptive cruise control system. The authors propose a reinforcement learning technique for the control of the throttle to maintain the desired inter-vehicle gap.

Girard et al. [5] propose a hierarchical implementation of a control architecture for cooperative cruise control (CACC). Some of the interesting features of their approach includes the ability to switch between various modes of operation depending whether the nearby vehicles are also equipped with CACC-capable devices. In addition, this system also implements cooperative forward collision warning (CFCW), through which the following vehicles receive information about the sudden braking of the vehicle in front.

3. CONVOY FORMATION MECHANISMS

Our interest in convoy formation mechanisms are two-fold. On one hand, we wish to model the driving behavior existing on current highways, as a result of manual driving, traditional cruise control systems and a small minority of vehicles equipped with intelligent cruise control. On the other hand, we are interested in designing new algorithms for the cooperative cruise control systems of near future. Note that for the foreseeable future, vehicles with different level of autonomy will share the same road. In fact, even if a vehicle has an intelligent/collaborative cruise control system, the driver might choose not to turn in on. For the sake of uniform treatment, in the following discussions we will use the term "vehicle" to cover both vehicles under the control of human driver and agents.

There are three different aspects of the participation of a vehicle in a convoy.

- The **decision to join or leave the convoy.** The vehicle can join any convoy in its physical proximity, or it can decide to drive outside of any convoy. For the sake of a uniform treatment, we will consider the later as the vehicle forming its own convoy.

- The **influence of the convoy on the vehicle**. Once the vehicle has joined a convoy, its driving is influenced by the presence of the other vehicles in the convoy. Most importantly, its speed needs to be synchronized with the speed of the other vehicles. Small, temporary adjustments in speed can be used to achieve the desired following distance / time gap between the vehicles.

- The **influence of the vehicle on the convoy**. In the simplest example, the leading vehicle determines the speed of the convoy, while the other vehicles do not have any influence. As an example of visual communication, a vehicle in the rear might be able to "pressure" the vehicle in the front to increase the speed. In the vehicles are connected through a vehicle-to-vehicle communication system, they will be able to reach a negotiated agreement about the speed of the convoy, following distance, order of the vehicles and other factors.

3.1 Convoy joining policy

In the following we introduce an algorithm for modeling the policy of the agents for convoy joining. This is both an algorithm for practical implementation [6], as well as a model of the human behavior in convoy joining.

The policy we are proposing is based on the measuring of the utility of the different convoys. Whenever a driver needs to make a decision (whether to join a convoy, leave a convoy, or move from one convoy to another) it will evaluate the utility of the convoy and pick the choice with a higher utility. As the utility of a convoy varies in time, the vehicle needs to perform periodic evaluations of the utility of the current convoy. Different vehicles can have different utility functions even if they are part of the same convoy. Vehicles in a convoy, however, need to agree on the same rules for evaluating influences, otherwise the integrity of the convoy can not be maintained.

We assume that the utility of a convoy depends only on the speed of the convoy and the parameters of the vehicle[2]. We assume that a vehicle V_i has a current speed P_i and desired speed D_i. The vehicle also has an upper speed limit H_i (determined by physical or legal factors, or simply by preference) and a lowest accepted speed L_i (normally determined by preference but also by fuel economy considerations).

It is desirable to have a utility function return 0 for convoys whose joining is not feasible for the vehicle and preferably high values for convoys which are close to its desired speed. A simple expression for the utility of the convoy with speed S_i for a vehicle V_j which satisfies this requirement is the following:

$$U = \begin{cases} 1 - \frac{|D_j - S_i|}{D_j} - \lambda \cdot \frac{|P_j - S_i|}{P_j} & \text{if } L_j \leq S_i \leq H_j \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Note that any offered speed that lies outside the lower and upper speed limits has zero utility. Otherwise, the utility of an offered speed is affected by two factors. The *compromise factor* $\frac{|D_j - S_i|}{D_j}$ determines the amount of compromise that the vehicle needs to make to become part of the convoy. It increases with the difference between the desired and the offered speed of the vehicle. Thus, an offered speed that is either higher or lower than the desired speed, will cause the utility of the offer to become lower. The *join cost factor* $\lambda \cdot \frac{|P_j - S_i|}{P_j}$ is the cost of joining convoy C_i, and it is zero if V_j is either currently a member of the convoy or if the offered speed matches the current speed of the vehicle. This factor reflects the need to accelerate or decelerate to join a convoy. In addition, this factor allows us to introduce "friction" in the behavior of the vehicles. By making it expensive for a vehicle to leave a convoy, we can reduce the number of defections and stabilize the convoys. Experimentally, we found $\lambda = 0.1$ to be an adequate value.

3.2 Influences among the members of the convoy

Let us now consider the next component of the convoy formation, the influences among the members of the convoy. We will consider three influence strategies.

Influence Strategy ASL (Adjusting to the speed of the leader): This is the traditional case of convoys formed by human drivers, or vehicles with intelligent cruise control systems. The advantage of this approach is that joining the convoy does not require negotiation. Furthermore, vehicles leaving or joining the convoy will not change the convoy speed. This means that the utility of the convoy remains the same for a vehicle throughout the lifetime of the convoy, increasing the stability of the convoy. The only reason for a vehicle to reconsider its convoy joining decision is if the convoy passes next to another convoy with a higher utility for the particular vehicle.

The disadvantage, however, is that the speed of the convoy is dictated by its slowest vehicle.

Influence Strategy AVG (Average desired speed):

In this influence strategy the protocol calls for the participating members to compute the average of their desired speeds, and then all members adjust to that speed. Naturally, this requires communication. The speed needs to be recalculated every time a vehicle joins or leaves the convoy. This phenomena is mitigated somewhat by the fact that the vehicles which join will likely have a desired speed close to the current speed of the convoy. The change in the speed of the convoy, in addition to the inconvenience of accelerating or decelerating, also poses the potential problem that by changing the utility of the convoy, it can reach a point where it is not worth for a given vehicle to remain in the convoy. If the vehicle decides to leave the convoy, this would lead to yet another speed adjustment, which, on its turn, might lead to further vehicles leaving. This way, a convoy spontaneously splits into a slower and a faster convoy.

Influence Strategy SPF (Social potential fields): Social potential fields [9] are a distributed behavior control scheme based on the idea of applying artificial forces among agents to keep them in group formation. In a social potential field, we have an artificial force between each pair of agents which can be described as the sum of an attractive and repulsive component, both being inverse polynomial with the distance. The movement of the vehicle is determined by the sum of the forces acting on the vehicle. The formula we used for the force between two vehicles with the inter-vehicle distance r:

$$F(r) = \frac{-c_1}{r^{a_1}} + \frac{c_2}{r^{a_2}} \quad \text{where} \quad c_1, c_2 \geq 0, a_1 > a_2 > 0 \qquad (2)$$

where a_1, a_2, c_1 and c_2 are user-defined constants. We assume that the forces are active only between the vehicles which are part of the

[2] A human driver might consider various other factors. A driver might be reluctant to follow a driver whose behavior appears to be erratic, or a large truck obscuring visibility. Drivers might be offended by the bumper stickers on the previous car.

Table 1: Example scenario configuration

Simulation parameter	Value		
Highway length	1 km		
Number of vehicles	5		
Communication range	50m		
Vehicle configuration	ID	Position	Speed(m/s)
	1	800	20
	2	600	28
	3	400	25
	4	200	32
	5	0	35

same convoy and in communication range of each other. Although more complex than the previous approaches, the influence strategy based on social potential fields has the following advantages:

- The convoy speed is dependent on the force parameters and can be adjusted using the parameters c_1, c_2, a_1 and a_2.
- The influence mechanism is able to regulate the inter-vehicle distance in the convoy.
- The influence mechanism does not suggest abrupt changes in the speed of the vehicles.

As the forces are dependent on the distance, the SPF influence strategy requires the knowledge of inter-vehicle distances.

3.3 An example

To illustrate the various phenomena at work, let us consider a small scenario which implements the SPF influence strategy and the proposed convoy joining policy. This example includes only 5 vehicles V1..V5 over a timespan of 10 seconds. While this simulation was performed with the same implementation used in Section 4, in this example we handcrafted the initial state of the scenario to illustrate as many interesting events as possible over a short timespan. The parameters of this scenario are listed in Table 1.

We recorded the evolution of the speed and position of each vehicle. To achieve a better visualization of the configuration of the convoy, our position graphs represent the *relative position* of the vehicles in relation to the last vehicle. The reason for this visualization approach is the fact that the relative movements of the vehicles are small compared with their common longitudinal movement, which would tend to dominate the absolute position plot.

Figure 1 shows the results of the scenario run, using the *SPF* influence algorithm. The top graph represents relative movement (with the origin of the relative coordinate system attached to V5), while the bottom graph represents the speed of the vehicles. The time scales are aligned to facilitate the observation of the correlation between speed changes and vehicle position. The thin lines represent the position of the vehicles if they choose not to join any convoy. This requires the vehicles to overtake the preceding vehicle even if the desired speed difference is small. In our case we have several overtakings (shown by intersecting thin lines). The bold lines represent the evolution of the vehicle locations with the assumption that the convoy formation mechanism is working.

Let us outline the series of events in the scenario:

- The vehicles start at time 0 with 200m distance between them. No convoy is formed as none of the vehicles are in each other's proximity. In absence of any convoy formation mechanism the speed of the vehicles is constant (shown by horizontal lines).
- V1, having a higher speed, approaches V2 from behind. Once they reach into each other's proximity, they agree to form a convoy and they adjust their speed through the SPF mechanism. This is a gradual process through which the speed of V1 is decreasing, while the speed of V2 is increasing. The speed of the vehicles settles at the agreed convoy speed at the moment when they achieve their desired following distance.
- Similarly, V3 approaches V4 from behind. They agree to form a convoy {V3, V4}.
- The convoy {V3, V4} is approached from behind by vehicle V5, which joins the convoy. This requires an increase of speed for V3 and V4 and a decrease of speed for V5.
- Finally, the convoy {V1, V2} is approached from behind by the convoy {V3, V4, V5}. The vehicles agree to merge the convoys, which requires V1 and V2 to increase the speed and V3, V4 and V5 to decrease.

The result is a convoy of 5 vehicles with a uniform speed and uniform inter-vehicle distance.

4. SIMULATION STUDY

In the following, we describe the results of a series of experiments in which we simulated the behavior of vehicles on a stretch of road using various convoy formation approaches. The simulation was implemented in the Java based Yet Another Extensible Simulator (YAES) [2] framework.

We have maintained the same convoy joining decision mechanisms across our experiments, but varied the influence mechanisms. The reason for this choice is that the decision of joining a convoy is, and will likely remain for a long time a decision of the human driver. However, once the convoy joining decision is made, the small adjustments will likely be delegated to the cruise control mechanism (traditional, intelligent or cooperative). At the first glance, it appears that identical convoy joining strategies would create identical sets of convoys (potentially with different speeds). It turns out, however, that this is not true over time. Starting from independent vehicles, indeed, the first set of convoys are formed in an identical way. Later, however, when, for instance vehicle V4 makes the decision whether to join the convoy {V1, V2, V3} the decision is based on the speed of the convoy, which is function of the influence mechanism. As a result, the set of convoys will diverge over time, and the different influence mechanisms may create a completely different macroscopic picture of the highway. As we had seen, current vehicular traffic essentially uses a form of ASL influence (even if the vehicles are equipped with intelligent cruise controls).

The question we are trying to answer is whether any of the more complex, collaboration based mechanisms (such as AVG or SPF) can achieve a better performance. Note that we are not interested in the behavior of the individual vehicles, but in the overall picture of the traffic: is it safer, more fluent, faster?

The parameters of the simulation are listed in Table 2. For these experiments, we considered a 60km long stretch of the highway with the number of vehicles ranging from 100 to 900 modeling various vehicle densities and traffic conditions. The data was collected by observing the traffic conditions for 600 seconds. The simulations were repeated 100 times with random initial conditions and the average values and the 95% confidence intervals were calculated.

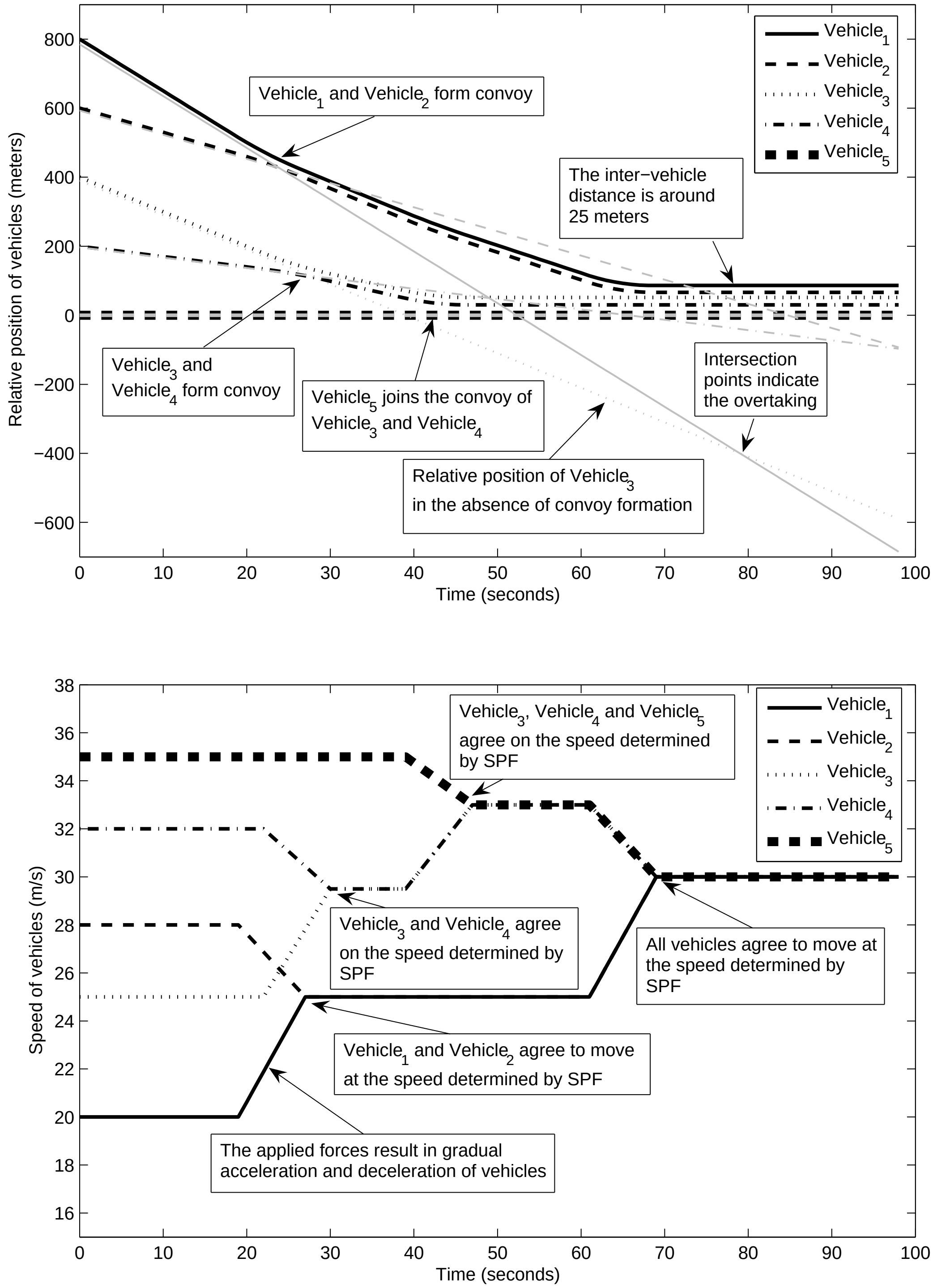

Figure 1: Convoy formation with the *SPF* influence mechanism. Top: relative position of the vehicles with respect to Vehicle-5. Thin lines: without convoy formation, thick lines: with convoy formation. Bottom: the evolution of the speed of the vehicles during convoy formation.

Table 2: Highway configuration used for the simulation

Simulation parameter	Value
Highway length	60 kilometer
Number of vehicles	100-900 vehicles
Vehicle initial speed	Uniformly distributed between 10m/s to 40m/s
Vehicle desired speed	Uniformly distributed between the vehicle's initial speed to 40m/s
Vehicle communication range	50m

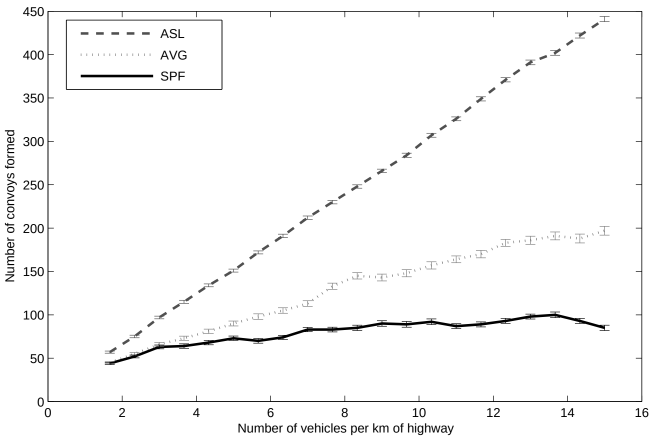

Figure 2: The number of convoys as a function of the density of the vehicles on the highway. The number of convoys formed increase with the density of the vehicles. The *ASL* and *AVG* approaches result in large number of convoys. The *SPF* approach results in the lowest number of convoys.

4.1 Number of convoys formed

Figure 2 shows the number of convoys function of the density of the vehicles. This number includes single-vehicle convoys, thus it is practically the number of independently operating units on the highway. Obviously, for a given traffic situation, the lower this value, the better, as it leads to a more fluent traffic. However, these results can not be interpreted in isolation, as it is also important to consider how well the speed of the convoy reflects the desires of the vehicles. For instance, a large convoy moving at the speed limit is desired, whereas a convoy formed of vehicles stuck behind a slow moving vehicle is not.

We find that the number of convoys vary greatly among the various influence strategies. With the *ASL* and *AVG* approaches, the number of convoys increases approximately linearly with the density, with the *AVG* approach creating about half as many convoys as the *ASL* approach.

The *SPF* approach, however, maintains a roughly constant number of convoys, in fact the number of convoys even show a slight, but noticeable decrease at high densities.

4.2 Distribution of convoy sizes

Figure 3 shows the distribution of the convoy sizes after the elapse of 600 seconds of simulation using 900 vehicles. As the size of the convoys ranges from 1 to 110, for sizes above 10 vehicles we have clustered them in groups of sizes 11-30, 31-50, 51-70,

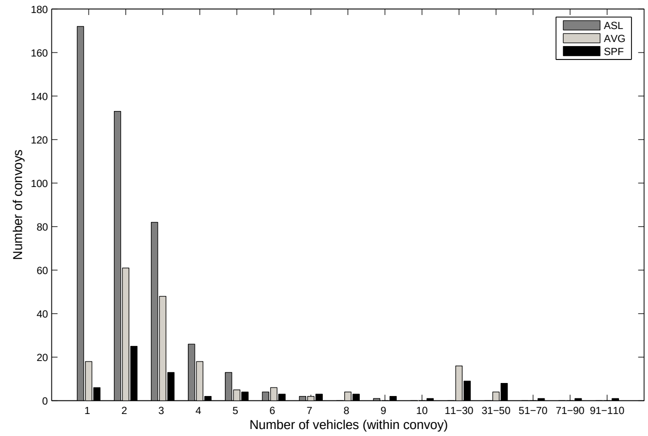

Figure 3: Distribution of the convoy sizes using a simulation involving 900 vehicles.

71-90 and 91-110.

For the *ASL* influence mechanism, the most frequent case is convoys of size 1 (i.e. vehicles which are not part of any convoy), followed by convoys of 2 and 3 vehicles. From here, the number of convoys continues to drop very quickly. There were no convoys of 10 vehicles or more formed with the *ASL* influence mechanism.

For the *AVG* approach, the largest number of convoys had the size of 2 vehicles, followed by 3, 4 and finally 1 vehicle. The *AVG* approach allowed the occasional formation of larger convoys as well, up to the 31-50 vehicle range.

Finally, the *SPF* approach also shows the largest number of convoys consisting of 2 and 3 vehicles. However, the *SPF* influence mechanism allowed the creation of several very large convoys, up to the 90-110 vehicle range (naturally, as there are only 900 vehicles in the experiment, there can not be a very large number of convoys of this size).

The conclusion of this experiment is that every influence mechanism produces a different distribution of the convoy sizes. The *ASL* mechanism favors small convoys or even individual vehicles (note that our experiments did not model "convoys by necessity" where vehicles get stuck behind a slow moving vehicle). The *AVG* and *SPF* mechanisms prefer larger convoys with 2-4 vehicles, with an occasional larger convoy of up to 50 vehicles for *AVG* and up to 110 vehicles for the *SPF*.

4.3 Distribution of convoy speed

Figure 4 shows the distribution of the convoy speed at the end of 600 seconds of simulation using 900 vehicles. For better visualization, we have clustered the convoys in the speed ranges of 0-4, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39 and 40-44 (m/s).

We did not consider aspects of the highway traffic such as speed limits, or the risks of high speed driving, aspects which should not normally be regulated through the convoy mechanism. Under these assumptions, the higher the average speed of the vehicles, the better for the traffic.

With the *ASL* influence mechanism, the highest percentage of convoys are moving at the very slow speed of 10-14 m/s, followed by a smaller and smaller percentage of convoys moving at higher speed. A very minute percentage of convoys move at speed 30 m/s or higher.

With the *AVG* influence mechanism, the highest percentage of

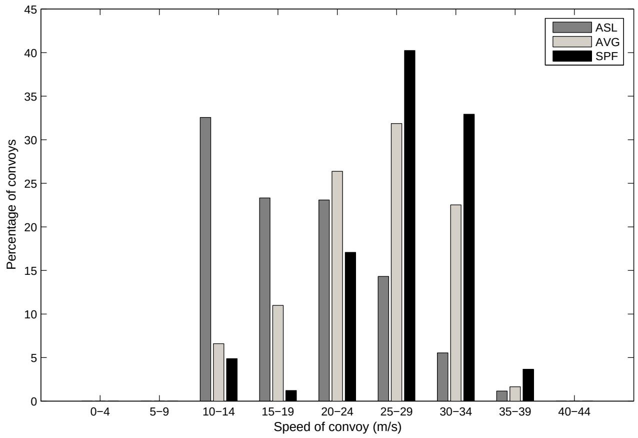

Figure 4: Distribution of the convoy speed using a simulation involving 900 vehicles.

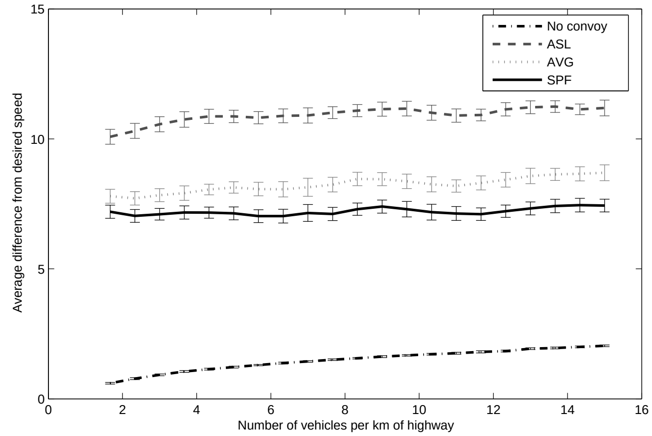

Figure 5: The average difference of the desired speed of the vehicles from their measured speed.

convoys are moving at the speed of 25-29 m/s, followed by the convoys moving at speed 20-24 m/s and then 30-34 m/s. A very small percentage of convoys move at the slow speed of 10-14 m/s or the highest speed of 35-39 m/s.

And finally, with *SPF* influence mechanism, the highest percentage of convoys are moving at the speed of 25-29 m/s, followed by a considerably large percentage of the convoys moving at the speed of 30-34 m/s.

So, the *ASL* mechanism favors convoys moving at very slow speed while both *AVG* and *SPF* approach favor faster moving convoys. The percentage of convoys moving at the speed of 25m/s or higher is largest with the *SPF* mechanism.

4.4 Average difference between measured and desired speed of the vehicles

From the point of view of the individual vehicle, the ideal driving environment is one in which the vehicle is alone on the road. In this situation, a vehicle would simply drive at its desired speed. When sharing the road with other vehicles, the agent might either form convoys, or attempt to achieve its desired speed by overtaking all the slower vehicles, irrespectively of the speed difference. On most roads, the act of overtaking in itself involves a certain amount of delay. Furthermore, a traffic environment where every vehicle is attempting to overtake all slower vehicles becomes highly chaotic and unsafe. On the other hand, convoy driving requires the vehicle to adjust its speed to the convoy, thus renouncing to its desired speed in exchange for the safety and predictability of convoy driving. In general, the lower the difference between the desired speed of the vehicle and the actual speed of the convoy, the better the convoy formation model is.

Figure 5 shows the average difference between the vehicles' measured and desired speed. The data used to plot this graphs was obtained by observing the middle 60 vehicles from a group of 900 vehicles moving on the highway. This was done to avoid the perturbations which occur at the periphery of the simulation environment. For instance, a fast vehicle at the front of the simulation would not have any slow vehicles in front of it, a fact which is an artifact of the simulation setup and it would reduce the accuracy of the measurement. The no-convoy graph was obtained under the assumption that all the vehicles in the traffic are trying to maintain their desired speed by overtaking all slower vehicles. We assumed that every overtaking incurs a small delay. Thus, with a large number of vehicles on the road, even the "no-convoy" approach does not guarantee the vehicle to move with its exact desired speed.

The graph shows that the smallest compromise is obtained by the "no-convoy" approach, followed in order by *SPF*, *AVG* and *ASL*. We can see that the collaborative convoy driving approaches *SPF* and *AVG* require a significantly lower amount of compromise between the actual and desired speed. This is a direct consequence of the fact that for these approaches all the vehicles in the convoy contribute to the choice of speed. This is a significant result because it provides strong motivation for the development of the collaborative convoy driving devices, and it makes it likely that the drivers will actually use them, as they can achieve speeds much closer to their desired speed compared to other approaches.

Convoy formation requires the vehicles to compromise over their desired speed. The *ASL* approach results in a large difference from the desired speed, because the vehicles will agree on the slow speed of the front vehicle. The *AVG* approach is somewhat better, while the *SPF* approach shows the smallest difference. This means that the *SPF* approach allows the vehicles to drive the closest to their desired speed. This is because *SPF* based convoys tend to agree on higher than average speed and the vehicles generally have the desire to move at higher speed. Also the utility function guarantees that vehicles do not join convoys that have large difference from their desired speed.

4.5 Number of overtakings

Figure 6 shows the number of overtakings as a function of the density of the vehicles. In general, the smaller the number of overtakings, the safer the traffic. The data used to plot the graphs was also obtained by observing 60 vehicles in the middle of the highway.

As expected, in the absence of any convoy formation approach, there are large number of overtakings. This number increases with the density of the vehicles. As expected, the number of overtakings are reduced by using the convoy formation approaches. The number of overtakings are the smallest for the *SPF* approach, followed by *AVG* and *ASL*. This can be attributed to the larger convoy sizes resulting from the *SPF* approach. While the number of overtakings increases with vehicle density for all three approaches, the increase is the slowest for SPF, making it the most scalable approach.

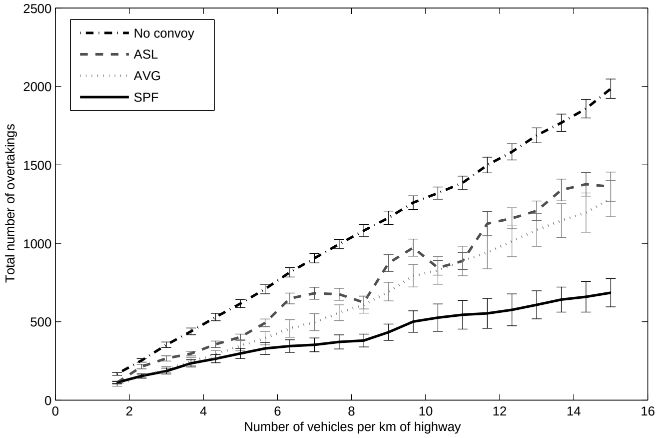

Figure 6: The number of overtakings as a function of the density of the vehicles.

5. CONCLUSIONS

It is a well-known fact that convoy driving has a beneficial effect on the fluency of the traffic, improving safety, and (in average) reducing traveling time. Naturally, convoy driving can be accomplished without the mediation of communicating agents, by adapting to the speed of the previous vehicle (which is the equivalent of the *ASL* strategy). This is the approach taken both by human drivers, as well as intelligent cruise control systems. For more complex strategies, however, it is necessary for vehicles to exchange information with each other. The *AVG* and *SPF* influence strategies we proposed can not be accomplished without inter-vehicle communication.

Our experimental results show that these collaborative strategies have significant benefits by allowing the formation of larger convoys, bringing the average speed of the convoys closer to the desired speed of the participating agents and reducing the number of overtakings.

As we had seen, the technical means for a widespread deployment of the collaborative cruise control systems will become available in the near future. These will likely by dual-control systems, where the decision to join a convoy will be under the control of the human driver, while the speed adjustments necessary to maintain the convoy and the communication necessary to determine the overall convoy speed will be under the control of the agent. As we had seen, even very simple convoy influence mechanisms can yield significant improvements in overall traffic behavior. More complex influence mechanisms, based on advanced negotiation models, global traffic awareness and so on will bring a new set of research challenges.

Acknowledgments

This research was sponsored in part by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-06-2-0041. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation heron.

6. REFERENCES

[1] N. Bellomo and M. Delitala. On the mathematical theory of vehicular traffic flow I: Fluid dynamic and kinetic modelling. *Mathematical Models and Methods in Applied Sciences*, 12(2):1801–1843, 2002.

[2] L. Bölöni and D. Turgut. YAES - a modular simulator for mobile networks. In *Proceedings of the 8-th ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems MSWIM 2005*, pages 169–173, October 2005.

[3] D. Chowdhury, L. Santen, and A. Schadschneider. Statistical physics of vehicular traffic and some related systems. *Physics Reports*, 329(4-6):199–329, 2000.

[4] K. Dresner and P. Stone. Multiagent traffic management: A reservation-based intersection control mechanism. In *In The Third International Joint Conference on Autonomous Agents and Multiagent Systems*, page 530âĂŞ537, July 2004.

[5] A. Girard, J. Sousa, J. Misener, and J. Hedrick. A control architecture for integrated cooperative cruise control and collision warning systems. In *Proceedings of the IEEE Conference on Decision and Control*, 2001.

[6] M. Khan and L. Bölöni. Convoy driving through ad-hoc coalition formation. In *Proceedings of IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), San Francisco, California*, pages 98–105, Los Alamitos, CA 90720-1314, March 2005. IEEE Computer Society Technical Committee on Real-Time Systems, IEEE Computer Society Press.

[7] J. Laumonier, C. Desjardins, and B. Chaib-draa. Cooperative adaptive cruise control: a reinforcement learning approach. In *4th Workshop on Agents in Traffic And Transportation, AAMAS'06*, Hakodate, Hokkaido, Japan, 2006.

[8] S. Paveri-Fontana. On boltzmann-like treatments for traffic flow: a critical review of the basic model and an alternative proposal for dilute traffic analysis. *Transportation research*, 9:225, 1975.

[9] J. Reif and H. Wang. Social potential fields: A distributed behavioral control for autonomous robots. In *Proceedings of International Workshop on Algorithmic Foundations of Robotics (WAFR)*, pages 431–459, 1995.

[10] K. N. und M. Schreckenberg. A cellular automaton model for freeway traffic. *J. Phys. I France*, (2):2221–2229, 1992.