An Initial Analysis of Operational Emergent Properties in a Platooning System-of-Systems

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***Abstract*—As systems-of-systems start to be more common in commercial applications, an analysis of emergent properties related to utility and cost for all stakeholders becomes critical. This paper describes an approach for this based on network simulation and game theory, which is applied to truck highway platooning. The emergent properties of energy efficiency and transport efficiency are studied as a consequence of the strategies for platoon formation, and it is shown that having information about the route planning of other vehicles has a significant positive effect on the properties. This indicates the need for a mediator in the platooning system-of-systems architecture. Its role is to communicate plans of the constituent systems.**

***Index Terms*—System-of-systems, platooning, emergent properties, game theory, architecture.**

I. Introduction

Systems-of-systems (SoS) is a term used to denote independent systems that collaborate to achieve something they cannot do on their own. The concept, with its origins primarily in the defense sector, is now rapidly becoming increasingly relevant in a large number of commercial applications as a result of the software-driven digitalization and automation of industry and society. Examples exist in domains such as transportation, energy, health care, manufacturing, smart cities, etc.

The defining characteristics of an SoS were described by Maier [1], and include *operational and managerial independence*, meaning that elements can make decisions on their own, and *emergent behavior* on the SoS level.

With the increasing usage of SoS in commercial applications, a cost-benefit analysis becomes critical, in which different decision options are evaluated in relation to various positive (i.e., benefit, utility or value) and negative (i.e. cost) criteria. The challenges of SoS cost-benefit analysis are in particular a consequence of the managerial independence. This means that the owners of different constituent systems make decisions, based on how they perceive their own utility and costs. However, since the decisions of different stakeholders depend on each other, this can lead to sub-optimal behavior on the SoS level, and create a non-desired emergent behavior when it comes to the cost-benefit balance of the SoS as a whole. The result can be that the SoS is unattractive to certain participants, who then choose to not participate, and thus undermine the existence of the SoS as a whole. To cope with this, it is necessary to design an SoS so that it provides sufficient value to all participants individually, as well as to the SoS as a whole, and this design problem requires good analysis methods.

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A. Case Study

To investigate the principles of SoS cost-benefit analysis, a case study has been used consisting of a truck highway platooning application. The idea of platooning is that a lead vehicle, which is driven manually, is followed closely by a number of other vehicles using automated driving. The benefit is that aerodynamic drag can be substantially reduced by shortening the distance between the trucks, leading to lower energy consumption. A key technology is the use of short-range radio communication between the trucks to control the speed of each truck, and thus the distance between them. In some proposals for platooning concepts, there is also a central mediator who coordinates formation of platoons, and can put restrictions on when and where platooning is allowed [2].

B. Research Questions

The contribution of this paper is to investigate a suitable approach for SoS cost-benefit analysis, and this is achieved by studying platooning as an example. This leads to the following more detailed research questions:

1) How is *energy efficiency* affected by different platooning characteristics? This is the expected benefit.
2) How is *transport efficiency* affected by different platooning characteristics? This is a potential cost.

The research method applied here is a theoretical analysis, since platooning has not yet been deployed in practice (with a few exceptions, [2]) and hence little or no empirical data on large scale effects is available. Therefore, we instead build mathematical models of the system using networks and game theory [3]. To study the effects of different factors, we apply numerical simulations, using both randomized data and data from real road networks and traffic scenarios. Most likely, a similar approach is relevant in many SoS, where the effects need to be investigated prior to actually building the system.

C. Paper Overview

In the next section, some aspects of viewing platooning as an SoS is discussed, in particular the system hierarchy and emergent properties. Then, in Section III, the operational context is described, showing how road networks and traffic are modeled. In Section IV, this context is populated with vehicles to capture their movements over time, from which the emergent properties can be derived. The analysis relies on simulations, as presented in Section V. These simulations are used in Section VI to evaluate the emergent effects of different decision strategies on the operational level. Then it is discussed how the findings can be generalized to other SoS in Section VII, and how they relate to previous research in Section VIII. Finally, Section IX summarizes the conclusions and discusses future extensions of this research.

II. Platooning as an SoS

The cost and benefit of an SoS are emergent properties that come as a result of a system hierarchy. In this section, the hierarchical decision levels are described both for SoS generically and for platooning in particular, and then the platooning emergent properties are introduced.

A. Hierarchy and Decision Levels

When studying different SoS, a hierarchical structure forms a suitable basis for reasoning about emergence:

- At the highest level are *strategic decisions*, involving both the mechanisms of the SoS as such, and decisions whether to prepare a certain system for being able to become a constituent. It is thus an existential decision for the SoS. In the platooning case, this includes the decisions made by the vehicle manufacturer regarding whether to develop platooning equipment for their products.
- At the level below, *tactical decisions* are made, and these are typically of a managerial character, and thus involve the organizations that own the constituent systems. The decisions relate to whether this particular organization should engage in the SoS. For platooning, this is the level where the haulage company makes decisions whether to equip their trucks for platooning or not.
- At the next level are the constituent systems, and at this level, a number of *operational decisions* are made, either automatically by a technical system or by its operators. In the example, the constituent systems are the trucks, and the decisions are made automatically or by the driver.
- At the bottom is the *operational context* of the SoS. The elements of the context are not considered parts of the SoS, and the stakeholders of the SoS do not have the power to modify it, but it has to be accepted as is. In the platooning example, this corresponds to the road and traffic environment in which the platoon will operate.

In addition to this, more levels can be added. For instance, there is a societal level, where authorities can make decisions that affect the decisions at lower levels. This could concern investments in road infrastructure to make platooning easier or safer; legislation regarding how platooning should be carried out, and its relation to other traffic; subsidies if there is a desire to stimulate a quicker introduction of platooning; and regulations to avoid lock-in effects that could make it difficult to create platoons with trucks of different brands or from different haulers. The reason authorities could have an interest in these actions is that the energy saving and pollution reductions of platooning are benefiting society as a whole.

The levels described here resemble the ones introduced in [4], which uses a generic terminology of Greek letters (α, β, γ, δ) to denote the levels from the bottom up.

In this paper, the focus will be on the operational decisions and the operational context. The analysis on that level forms input to the analysis of higher level decisions.

B. Emergent Properties Representing Cost and Benefit

As described above, energy and transport efficiency represent key emergent properties of platooning. The overall energy efficiency, or fuel consumption for conventional vehicles, is a direct consequence of how much time is spent in platooning compared to solitary driving. The indicator to use is thus the proportion of total time that vehicles drive in groups with other vehicles, denoted by $\phi \in [0, 1]$. $\phi = 0$ means that no platooning takes place, and $\phi = 1$ that all vehicles always drive in platoons.

Transport efficiency is not affected by the actual platooning, but by the formation process, since vehicles sometimes will choose to wait for others in order to be able to form a platoon instead of driving alone. In practice, the cost of waiting includes the reduced utilization rate of the vehicles, the salary cost for having drivers wait, and the delayed delivery of the goods. The indicator $\tau \in [0, 1]$ is the proportion of time that vehicles move, where $\tau = 0$ means that all vehicles just wait all the time, and $\tau = 1$ when no vehicles ever wait.

ϕ and τ are indicators of the efficiency of platooning. As a reference, in the situation when no vehicles are equipped for platooning, $\phi = 0$ since no vehicles platoon, and $\tau = 1$ since vehicles never wait for each other.

It is interesting to investigate how certain factors influence the efficiency metrics. This includes properties of the road network and traffic intensities, since it can be assumed that platooning will require a certain traffic intensity to be meaningful and hence will only be applicable at certain parts of the road network. At the same time, platooning will not work well if the traffic intensity is too high, because that will lead to congestion where the reduced speed minimizes the fuel saving potential, and also makes it difficult to form platoons. Conversely, there could be other reasons, such as safety [5], that exclude a priori certain types of roads from platooning, e.g. restricting it to only motorways to allow other vehicles to safely pass a truck platoon. The proportion of vehicles equipped with platooning will be decisive for the ability to form platoons.

III. Road and Traffic Models

In order to analyze the emergent efficiency properties of platooning, and evaluate different decision strategies at the higher levels in the hierarchy, a model of the operational context in the form of roads and traffic is needed. The initial road and traffic models use a very simple graph, where the nodes represent junction points between roads, and the edges capture the distances and traffic flows of the roads between the junctions. This model is easy to relate to real data about roads and traffic, but less suitable for analysis of platooning. Therefore, it is then transformed into an analysis model for studying the emergent properties in the platooning SoS.

A. Road Network

It can be assumed that the road infrastructure consists of n junction points, which are modeled as nodes in a graph. Let R be an $n \times n$ matrix where each element $R_{ij} > 0$ indicates that there is a road of distance R_{ij} from node i to node j, and $R_{ij} = 0$ means that there is no direct road. The network is undirected, so $R_{ij} = R_{ji}$ (the distance is the same regardless of direction of travel) and $R_{ii} = 0$ for all i, since the distance from one place to itself is 0.

The distances are expressed as the number of time units it takes for a vehicle to travel between the nodes, so the edges in the graph thus represent the passage of time. This is under the assumption that all vehicles travel at the same and constant speed on a given road segment.

The degree of a node is the number of outgoing links, $d_i(R) = \#\{j \mid R_{ij} \neq 0\}$. A road network can be characterized by the statistical distribution of node degrees and distances. If $d_i(R) = 0$, the node is isolated, which is an irrelevant case in this application. $d_i(R) = 1$ means that the destination is at the end of the road, which certainly occurs in real road networks, although perhaps not that frequently. $d_i(R) = 2$ is an intermediate stop on a road, which is fairly common for a mid-size city, when taking only the highway network into account. $d_i(R) > 2$ represents a junction, where different possible routes can be chosen, and it can be expected that the higher the degree, the less common it is.

B. Traffic Intensity

Traffic intensity T_{ij} is measured as the average number of vehicles that leave a node i towards a node j in one time step. Obviously, the traffic intensity graph has the same structure as the road network graph since vehicles can only travel on roads, so $T_{ij} = 0 \Leftrightarrow R_{ij} = 0$ for all i, j.

The number of vehicles is assumed to be constant, so the sum of incoming vehicles to a junction i has to equal the sum of outgoing vehicles:

$$\sum_{j=1}^{n} T_{ij} = \sum_{j=1}^{n} T_{ji}$$

The total number of vehicles m in the system is given by the sum of the entry-wise product of R and T, since R indicates how long a vehicle stays on a road segment, and T indicates how many vehicles enter the segment at each time step:

$$m = \sum_{i=1}^{n} \sum_{j=1}^{n} R_{ij} T_{ij}$$

In this model, only vehicles that actually drive are included. In reality, there are many more vehicles, since a truck has to stop for loading and unloading, maintenance, etc. However, a stopped vehicle does not platoon, and it is thus irrelevant here.

The traffic intensity patterns can be characterized by the total number of vehicles and the statistical distribution of intensities on individual road segments.

An example of the R and T matrices, represented as graphs, is shown in Fig. 1a. In this example, $m = 34$.

C. Analysis Model

The model above is easy to match to available data on real road networks and traffic flows. However, it is not detailed enough to allow the derivation of the metrics for platooning efficiency. Therefore, it is transformed into a model that better captures the detailed location of each vehicle, to determine how many vehicles platoon at a given time step. Space does not permit a detailed explanation of the transformation, but only an overview is given through the example in Fig. 1.

The key idea of the transformation is that the passage of time will now occur in the nodes, which each represent one time step, whereas in the initial model time was associated with edges. Each road segment in R and T becomes a sequence of nodes in the $n' \times n'$ matrices R' and T', where the number of nodes corresponds to the road segment length. Travel direction needs to be represented, since vehicles only platoon with those going in the same direction, so each road segment is represented as two such sets of nodes.

The transformed road network matrix R' is binary, i.e. a 1 represents the existence of a link and a 0 the non-existence. The transformed traffic intensity matrix T', shown in Fig.1b, retain the same traffic on outgoing links from the original nodes as in T.

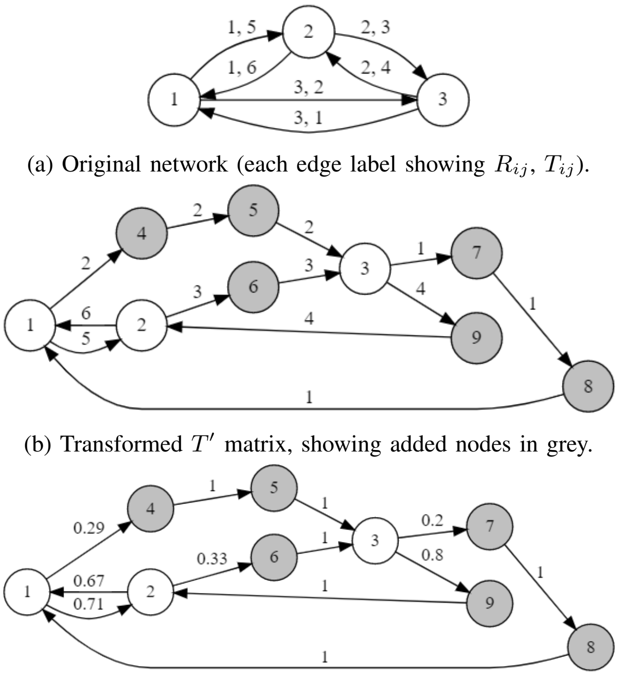
In the forthcoming dynamic analysis, where vehicles move around in the road network in such a way that they generate traffic intensities corresponding to the values in T and T', it will be useful to describe what the probabilities are of a vehicle selecting each of the outgoing links from a node. These probabilities will be captured in the matrix P, where P_{ij} is the probability that the vehicle will move to node j when in node i. The elements of this matrix are derived by normalizing the rows of T' so that each row sums to 1, which makes sense since it is assumed that all vehicles will move in each time step, i.e. they have to select one of the links:

$$P_{ij} = \frac{T'_{ij}}{\sum_{j'=1}^{n'} T'_{ij'}}$$

The matrix P captures all the necessary information that was originally in R and T, except the number of vehicles m. This means that we can now forget about R, T, R', and T' and work only with P. m is of course also needed, but since it is no longer encoded in the matrix, it can be varied to investigate effects of different traffic intensities.

In practice, P will be large, since every road segment is represented by many nodes. This also means that it will be very sparse, and the average degree of a node will be just slightly above 1, since the vast majority of nodes will be the ones added along the road segments, and these have degree 1.

Reasonable values for the duration of a time step is given by the fact that we will assume that the traveling distance during



(a) Original network (each edge label showing R_{ij}, T_{ij}).

(b) Transformed T' matrix, showing added nodes in grey.

(c) Transformed P matrix showing transition probabilities.

Fig. 1: Model transformation steps.

one step is so short that trucks within that distance of each other will choose to platoon, which means that they need to be close enough to establish short range radio communication, and this gives a distance of at most 1 km. At the same time, the distance should be long enough for a platoon to fit within it, which means that it should be at least 100 m. Given a typical truck highway speed of 90 km/h = 25 m/s, the truck will travel 100 m in 4 s, and 1 km in 40 s, which gives an idea about the plausible duration of a time step.

IV. Dynamic Models

Having described the analysis model for road networks, vehicles will now be added that travel around over time. With this, it can be investigated when platooning will actually occur and thus calculate the efficiency metrics. At each point in time, the system will have a certain state which captures where the vehicles are in the road network and where they plan to go.

A. System State

In the system, there are m vehicles, and at any point in time, each vehicle is in one of the nodes. This is represented by a vector v, where v_k is the current position of vehicle k.

In the platooning application, sometimes a vehicle may decide to stay at a junction in order to wait for platooning partners. The fact that a vehicle is waiting is captured by the vector w, where w_k indicates for how long vehicle k has been waiting for partners. Note that it is only possible to wait at a junction. The information about when vehicles choose to wait will be necessary later when calculating transport efficiency.

In reality, trucks do not travel around randomly, but they follow a planned itinerary, which is given by the destinations of the goods they are carrying. The plans of each truck will be represented explicitly, since that information can be useful to other trucks when deciding whether to wait for platooning partners or to continue. Assume that the plan stretches $L \geq 0$ time steps into the future. Then, Π is an $m \times L$ matrix where Π_{kt} represents the node where vehicle k thinks that it will be in t steps. The values of Π are node indexes, thus $1 \leq \Pi_{kt} \leq n'$.

The state of the dynamic model is represented by $s = (v(s), w(s), \Pi(s))$, and the set of states is denoted by S.

B. State Transitions

Transitions normally take a vehicle to the first state in its plan, and the plan is moved forward one step while adding a new last step. To ensure that the traffic intensities in T are reflected, the new last step will be selected randomly according to P. The waiting value $w_k = 0$ for that vehicle.

At junctions, we allow vehicles to make a decision, which is captured in the decision function $\delta : S \rightarrow \{0,1\}^m$, where the k:th element of the result is the decision made for vehicle k in that state. This function is used to determine whether to wait for platooning partners, in which case it is 1, or not to wait in which case it is 0. If there is already a vehicle at the node with the same initial plan, the vehicle will always proceed as described in the previous paragraph. If there is no such vehicle, the decision has to be made to either proceed alone, or to wait. If the vehicle chooses to wait, its new node will be the same as the current; the plan will be the same as before; and the waiting value is increase by 1.

C. Calculating Emergent Properties

Based on the dynamic model, it is now possible to formally define how to calculate the two metrics of interest, namely energy efficiency (ϕ) and transport efficiency (τ). For these calculations, it is necessary to know the number of vehicles that are currently traveling in each node i, which is denoted $\lambda_i(s) = \#\{k \mid 1 \leq k \leq m \wedge v_k(s) = i \wedge w_k(s) = 0\}$ for a given state s. Note that $\lambda_i(s)$ ignores vehicles that are waiting.

Based on this, the proportion of all vehicles traveling in platoons of length $l > 0$ in state s can be calculated as:

$$\phi_l(s) = \frac{\#\{k \mid 1 \leq k \leq m \wedge w_k(s) = 0 \wedge \lambda_{v_k(s)}(s) = l\}}{\#\{k \mid 1 \leq k \leq m \wedge w_k(s) = 0\}}$$

Here, $\phi_1(s)$ denotes the proportion of vehicles traveling alone. Now the proportion of all vehicles that travel in platoons in this state can be calculated:

$$\phi(s) = \sum_{l=2}^{m} \phi_l(s)$$

The upper limit of this sum is due to the fact that the longest possible platoon involves all m vehicles. Since all vehicles are either platooning, traveling alone, or waiting for partners, the transport efficiency $\tau(s)$, which is the proportion of vehicles driving, becomes:

$$\tau(s) = \phi_1(s) + \phi(s) = \frac{1}{m}\#\{k \mid 1 \leq k \leq m \wedge w_k(s) = 0\}$$

So far, the metrics have been calculated for one state. To give their aggregated value, it is necessary to calculate them for each visited state, and take the average. Assuming that the visited states are $s_0, s_1, \ldots$, the final metrics become:

$$\phi = \lim_{t\to\infty} \frac{1}{t}\sum_{t'=0}^{t} \phi(s_{t'}) \qquad \tau = \lim_{t\to\infty} \frac{1}{t}\sum_{t'=0}^{t} \tau(s_{t'})$$

V. Simulations

To calculate the metrics, simulations are used. In the analysis, we will to a large extent use randomly generated graphs of the road network and traffic intensities. One could of course argue that it is more relevant to instead use models of real road networks. However, each road network will only give one data point, which means that it is very hard from that to get an understanding of the relations between different characteristics. By instead analyzing a set of random networks, a more solid understanding about how different factors interact vis-à-vis the emergent properties can be achieved.

Given a random road network, traffic patterns have to be added. Since the dynamic model only relies on P, and does not use T and T' directly, we can skip generating those matrices and go directly for P. If there is still an interest in T or T', they can instead be reconstructed from the simulation data. To obtain P, the first step is to transform R into R' as described in Section III. Then, for each $R'_{ij} > 0$, let P_{ij} be a random number drawn from a given distribution. Finally, normalize P, by dividing each entry in P by the sum of its row.

A. Parameters for Network Generation

The network generation parameters are distributions to generate the number of nodes; number of links; distances between the nodes; and probabilities for the traffic. In addition, the traffic density is needed, i.e. how many trucks should be added. To find appropriate distributions for these it is illustrative to look at some real road networks in Sweden. The data gathered is based on public sources on the Internet; data from different authorities; and official statistics. It has been collected using a high-level approximate analysis, with the purpose of getting some feeling for the real-world situation without the need for exact numbers.

In Sweden, there is about 2 000 km of motorways. Motorway exits are numbered, and as an example, the E4 highway between the cities of Helsingborg and Gävle is about 740 km long and has about 130 exits, giving an average distance between exits of around 6 km. Assuming the same relation holds for the entire network, there should be around 350 nodes in R. There is about 15 places where the motorway ends, i.e. nodes with degree 1. The vast majority is exits to other roads or cities, i.e. nodes with degree 2, and only around 15 nodes have degree 3. The average node degree is thus around 2.

There are about $80 \cdot 10^3$ heavy trucks in the country, that drive around $35 \cdot 10^3$ km per year on average. Their average speed on motorways is 85 km/h (whereas the allowed maximum speed for trucks is 90 km/h). The total annual distance traveled on motorways for all categories of vehicles is $18 \cdot 10^9$ km, and the total distance traveled on all kinds of roads for all vehicles is $60 \cdot 10^9$ km, thus 30% of the traffic is on motorways. Assuming the same proportion holds also for trucks, that would mean that those trucks cover $80 \cdot 10^3 \cdot 35 \cdot 10^3 \cdot 0.3 = 840 \cdot 10^6$ km on motorways each year. Dividing this by the average speed, and by the number of hours per year, the conclusion is that about 1000 trucks are on average driving on the motorways at any point in time, or about 0.5 per km of road.

With the above data, the following input to the random generation of R and P can be used:

- The size of the network does not matter so much, as long as the vehicle density is kept. We will use a uniform distribution with values in the range $[20, 50]$ for n, giving networks of about 10 % the size of the Swedish network.
- For the number of links, we will use $1.05n$.
- The distances can vary quite a lot, and we will use a Poisson distribution with mean 5, and add 1 to the generated numbers to ensure that they are positive integers. The time step is 1 km.
- The weights used to calculate route selection probabilities in P come from a uniform distribution in the range $[0.2, 0.8)$, to ensure that there is some traffic on all roads.

B. Simulation Set-up

In the simulations, the following key factors were varied:

- The road network. We used a set of 20 different networks that were randomly generated using the algorithm and parameters described earlier in this section.
- Number of vehicles m. As a baseline, the data from Swedish roads of about 0.5 vehicles per km was used, and based on this, the number of vehicles for each random network was calculated. Then, the actual simulation was executed once for each of the following multiplier of that number of vehicles: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.0, 3.0. This is to study the effects of different take rates of platooning equipped trucks.
- The decision function δ and its parameters. This will be discussed further in Section VI, where different alternative decision functions and parameters are introduced.

Each combination of these factors was executed once, for 200 time steps, starting from an initial state where vehicles were randomly assigned to nodes using a uniform distribution, and where initial plans were randomized according to probabilities in P.

VI. Operational Decision Strategies

The decision the driver has to make is when to join or not join a platoon. If two or more equipped vehicles happen to be at the same place, they have nothing to loose by joining the platoon, so the analysis will assume that they always join when an opportunity arises. However, if no one else is around, the driver has the choice of waiting at the junction for others to show up, or continue on their own to the next junction. What decision to make depends on the likelihood of another platooning equipped vehicle turning up within a reasonable amount of time, which is a consequence of the platooning take rate, and hence of the haulers' decisions. It also depends on the decision by other drivers, i.e. whether they choose to wait at some earlier junction instead of continuing.

In this section, several decision strategies are studied:

1) Randomly choose in each time step whether to wait one step longer or not, with some probability of each decision. This is a speculative waiting strategy.
2) Use information about the plans of other vehicles to decide how long to wait.
3) Base the decision on whether to wait on the expected utility of doing so.

Each of these strategies will be captured through different definitions of the δ function, and they are described in the following subsections.

A. Stochastic Platooning

In stochastic platooning, the function $\delta_k^p(s) = 1$ with a probability of p, i.e. in each time step, vehicle k if at a junction with no platooning partners around will wait one more time step with a probability p, and not wait with probability $1-p$. Three cases can be identified, depending on the value of p:

- For $p = 0$, the vehicles will never wait, and this is what happens if platoons form spontaneously. In other words, if two vehicles by hazard come close to each other, they will start platooning and continue to do so as long as their routes match, but no other measures will be taken to increase the rate of platooning. Since no vehicles will ever wait, $\tau = 0$ in this case.
- In the case $p = 1$, a vehicle will always wait, and keep on doing so until a platooning partner shows up.
- For $0 < p < 1$, vehicles will wait for a random period of time, and if no vehicle turns up, it will eventually continue alone. The expected waiting time t can be derived as follows: In the first round, $\delta = 0$ means that the vehicle continues, giving an expected value of 0. If $\delta = 1$, a new round starts, which is independent from the previous, so in this case the expected value is $t + 1$. This means that $t = (1 - p) \cdot 0 + p \cdot (t + 1) \Rightarrow p = t/(t + 1)$.

In the simulations, the parameter p was varied to give different expected maximal waiting times, using the following values: 0.0, 0.5, 0.67, 0.75, 0.8, 0.91, and 1.0 for the waiting times 0, 1, 2, 3, 4, 10, and forever.

Fig. 2a and c show simulation data for stochastic platooning, where each curve represents a different setting for p used in δ^p. The x axis represents different numbers of vehicles m, using the multipliers of the baseline 0.5 vehicles per km of road. As can be expected, higher values on p yield higher values on ϕ and lower on τ, and both ϕ and τ increase with m.

It is interesting to see that even a little bit of waiting can have quite a large effect. Take the case where $m = 0.5$. If p is increased from 0 to 0.5, i.e. a vehicle will on average wait one time step (around 40 s) for a partner, then ϕ increases from less than 0.3 to almost 0.5, at the cost of decreasing τ from 1 to about 0.9. To obtain the same improvement of ϕ by increasing the population (e.g. by increasing platooning take-rate), more than a doubling of m is needed.

B. Planned Platooning

In stochastic platooning, no information is exchanged between the vehicles in order to facilitate the formation of platoons. This puts severe limitations on what effects can be achieved since there is no way for a truck to predict whether a partner will be available or not. To remedy this, one could let vehicles announce their current position and route plans to each other, and let the decision function take this into account.

Note that this adds a requirement that the platooning SoS must include an infrastructure for this communication. Since potentially a vehicle may exchange information with any other vehicle, the short-range radio used for vehicle-to-vehicle communication will not suffice, and instead cellular communication must be employed. Most likely, it will also include a centralized mediator that dispatches the information between vehicles, since otherwise all vehicles would need to communicate with all other vehicles.

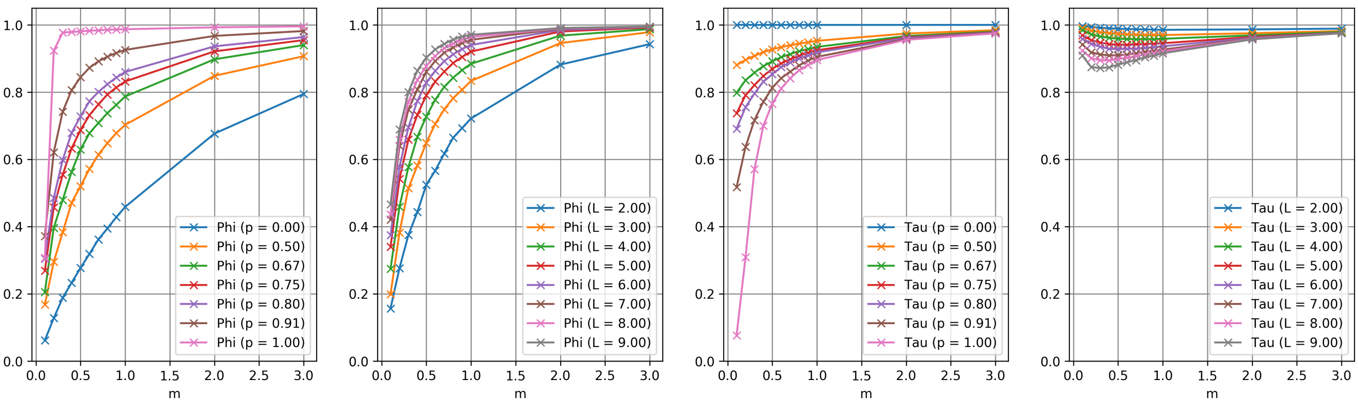
The information that can be communicated is essentially what is in the state of the model, i.e. current position and plans of the vehicles. (The information whether a vehicle is waiting or not is less valuable in this case.) The parameter of the decision function for planned platooning is the length L of the plans, determining what time horizon is relevant. The decision $\delta_k^L(s)$ will be 1 when there is another vehicle $k' \neq k$ that plans to arrive at the junction where k is now within $L-1$ time steps, and then continue in the same direction as k.

Fig. 2b and d show simulation data for planned platooning, with $L = 2, 3, \ldots, 9$. Looking at ϕ, it can be seen that even the shortest range plan has a distinct positive effect on ϕ compared to spontaneous platooning, and the longer range plans are approaching similar ϕ's as stochastic platooning with $p = 1$. However, when looking at τ, it can be seen that the cost of waiting is drastically reduced for smaller m, and in fact τ is bounded by a large number which is natural since vehicles will never wait longer than L.

From this, it can be concluded that exchanging information about plans has a large benefit in increasing platooning rate and bounding the cost, and the inclusion of a coordination mechanism in the SoS is thus needed. In particular, the effects are most significant at smaller values of m, and the coordination is therefore particularly important when platooning is first introduced since there is then only a small number of equipped vehicles in service.

C. Utility Based Platooning

In the previous cases, the decision strategies have tried to increase ϕ while striving to keep some control of τ. However, they have not included any analysis of the cost and benefit of different alternative decisions for the individual vehicle. The



(a) Stochastic platooning ϕ. (b) Planned platooning ϕ. (c) Stochastic platooning τ. (d) Planned platooning τ.

Fig. 2: Energy efficiency (ϕ) and transport efficiency (τ) as functions of multiples of m for different decision strategies.

planning decision functions have just looked at when another vehicle going in the same direction will show up at the current junction, and it does not take into account for how long they will both be going together. This could have the effect that a vehicle waits for another one, only to find out that they will go different routes already at the next junction. In that situation, it could sometimes be better to leave the junction alone even if some other vehicle is approaching, in order to possibly catch up with yet another vehicle at the next junction with which a longer lasting platoon could be formed.

In the case of utility based platooning, it becomes evident that the choice of one vehicle affects both the utility of itself, the utility of the other vehicles with which it could potentially platoon, and the efficiency of the whole system.

To illustrates this, consider a minimal road network with only two nodes, and with a distance of 1 between them. This network can be modeled by the following matrix:

$$R = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = R' = P$$

Assume now that there are two vehicles, and that initially one of them is in each node. If $\delta^{p=0}$ is used, they will just go back and forth between the nodes and never form any platoons, so $\phi = 0$ and $\tau = 1$. So obviously one of them has to wait for the other, and once that happens they will continue to platoon forever. The cost of doing so will be that one of them is delayed one step, and the other not. If the platooning goes on for t time steps, the cost is $\epsilon = 1/t$. In the long run, this cost is negligible, and they will both converge so that $\phi \to 1$ and $\tau \to 0$, but slightly quicker for the one not waiting.

The decision table for the corresponding game is as follows:

	V_2 Wait	V_2 Continue
V_1 Wait	$\phi_1 = \phi_2 = 0$ $\tau_1 = \tau_2 = 0$	$\phi_1 = \phi_2 = 1 - \epsilon$ $\tau_1 = 1 - \epsilon$, $\tau_2 = 1$
V_1 Continue	$\phi_1 = \phi_2 = 1 - \epsilon$ $\tau_1 = 1$, $\tau_2 = 1 - \epsilon$	$\phi_1 = \phi_2 = 0$ $\tau_1 = \tau_2 = 1$

Clearly, both would benefit if one of them chooses to wait, but if both choose to wait this is a worse situation than if both choose to continue.

Although the above example of a game on platooning is extremely simple, it illustrates that some coordination of decision making might be necessary to maximize utility of the vehicles, and also increase efficiency of the SoS as a whole. The example also shows that the utility might be unevenly distributed, in that one vehicle has to wait for the other, but once they form a platoon both benefit. There could therefore be a need for a re-compensation mechanism to distribute the waiting costs to both vehicles. In the same way, there might be a need for re-compensation between vehicles depending on in which order they drive in the platoon, since vehicles at the end get a higher energy reduction than those at the front.

The consequences of this is that a utility based decision function will in effect become a global optimization problem, where there will be an element of negotiation among vehicles as of how to distribute the waiting costs. The mechanisms for handling this will most likely have to be implemented in the central controller, which now becomes a platooning broker. Also, once a common plan has been made, some kind of contract is probably needed, to avoid situations where one vehicle takes the cost of waiting, just to find out that the intended platooning partner after a while decided to change its plans.

VII. Discussion

The analysis in the preceding sections have been specific to the platooning case, but the general techniques used are most likely applicable in other SoS settings too. As a first step, a systems thinking based analysis structuring the problem into multiple hierarchical levels helps identifying the kind of decisions involved, and allows a reasoning about emergence. It also clarifies the inter-dependencies between decisions.

In the more detailed modeling, networks were used, and this is generally interesting for SoS since they are about relations between entities. The constituent systems are modeled as agents, and the independent decisions need to be made explicit in order to apply stochastic simulations and game theoretic analyses to see the dynamic effects of the SoS as a whole under different decision strategies and different parameters.

When investigating different decision strategies, the kind of information exchanged between constituents is crucial, and the state, plans, and preferences are examples of such information that need to be considered. The actual decision strategy can have implications on the SoS architecture, such as the need to introduce additional mediators or central coordinators.

The case study also indicates that a "hen and egg" problem exists in general for collaborative SoS, in that the operational value of the SoS to a constituent increases with the number of participants. However, this means that the incentives for joining the SoS from its conception are very small, and hence there is a risk that the SoS never grows. This needs to be dealt with in the higher levels of the decision hierarchy, to encourage prospective participants to invest in the SoS.

VIII. Related Work

Vehicle platooning is a problem that has been studied over several decades, but the emphasis has been on longitudinal control algorithms [6].

When it comes to the cost-benefit analysis, a few papers have studied the reduction in aerodynamic drag [7] and in fuel consumtion [8], with results pointing to a reduction of about 5-10%, depending on the position of the vehicle in the platoon. These results are valuable input to our analysis, which is however focusing more on the platoon formation than the actual driving.

Regarding platoon formation, one proposed solution is to use controllers at major intersections that will give speed advise to drivers so that they can meet up at the same time [9]. The consequence of this is that a vehicle may need to increase its speed in order to catch up with others, and the cost of this has also been investigated [10].

Applying a combination of game theory, network models and simulation for SoS analysis has been suggested in a number of previous studies. This includes the study of consumer acceptance of smart electricity grids [11]. The strategies for joining or not joining a federative system from the point of a potential constituent has been modeled using the Stag hunt game, and it is suggested that the initial investment decision can be analyzed using real options [12]. Finally, the willingness to cooperate in an SoS has been modeled as a function of Sympathy, Trust, Fear and Greed which also led to the formulation of a Stag hunt game [13].

IX. Conclusions and Future Work

In this paper, we have presented an initial analysis of the operational decisions in a platooning SoS. It was shown that the choice of decision strategy by the drivers has a large effect on the emergent properties related to energy efficiency and transport efficiency, in particular if information about the route planning of other vehicles can be used for deciding when to wait for partners or not, something which requires a mediator in the form of a central system. It was also shown that more advanced planning easily leads into a situation where game theory needs to be applied to understand the effects of simultaneous decision making by the individual drivers, where there may be a need for re-compensation mechanisms to mitigate situations where individual selfish behavior will lead to reduced efficiency for everyone.

We plan to extend this work in several directions. First, on the operational level there is a need to elaborate further the game theory aspects of more advanced planning processes. Then, the other levels in the SoS hierarchy will be attacked, to understand how the haulers will make their investment decisions into platooning equipped trucks as a consequence of the efficiency that can be obtained. This in turn leads to the analysis of the vehicle manufacturer decisions about when to invest in product development, and what pricing strategies to use.

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