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DOI: 10.3217/978-3-85125-668-0-13

Real-Time Governance of Transportation Systems. A Simulation Study of Private Transport

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Abstract

For this study we developed a traffic-simulation based on the SimCo simulator tool and ran different governance scenarios regarding the effects of the distribution of real-time traffic data among drivers. The scenarios were based on interviews with experts from diverse fields, including a navigation service provider, the German Federal Highway Research Institute, and public transport providers. We found that a coordinated form of governance between private firms and local authorities benefits all parties. To analyse the impact of such a coordinated mode of governance, two scenarios were implemented. Firstly, drivers would get real-time traffic information and, secondly, they would also receive information on emissions enabling them to change their route accordingly. We found that the use of real-time data does indeed decrease traffic jams, and thus increases network efficiency, but it also increases emissions. This trade-off between network efficiency and emission reduction is prevalent in all our findings.

Keywords: algorithms, governance, self-determination, simulation, traffic

1 Introduction

While not entirely new, algorithmic governance of traffic has become a source of hope concerning the reduction of emissions and improved traffic flow. The increased use of navigation systems (either device, car or app-based) has led to a rise in both real-time traffic data and traffic management opportunities (e.g. by individualised routing suggestions). The resulting combination of centralised traffic management and decentralised decisions, which relies heavily on the real-time distribution of data, is a new mode of governance. To tackle this relatively unexplored issue, we seek to answer the following questions:

• How does the interplay of centralised governance and decentralised decisions work?

• How efficient is this mode of governance and can it be deployed to achieve political objectives?

We conducted guided interviews and consulted focus groups comprising representatives of navigation service providers, public transport organisations and the German Federal Highway Research Institute. Based on these interviews, we developed multiple governance scenarios. In one such scenario, drivers are equipped with a *smart navigation* system that shows the best routing option based on real-time traffic data. Another scenario combines this form of commercial navigation with governmental emission regulations in a *coordinated governance mode*. Using agent-based modelling (ABM), we transferred our findings to a simulation model to test various what-if scenarios and compare different modes of governance.

2 Theoretical framework

2.1 Multi-level governance

The underlying frameworks for our analysis are the macro-micro-macro-model and the model of social explanation (MSE) (Coleman 1990; Esser 1993a). In other words, the structure on the macro-level – recommendations that may or may not be followed – sets the frame for an individual's actions and influences them hereby. Interactions between individual actors on the micro-level of a system, e.g. drivers following recommended routes, then aggregate and influence the macro-level which then changes accordingly so, e.g. congestion can be avoided, emissions can be lowered, and net efficiency can be increased.

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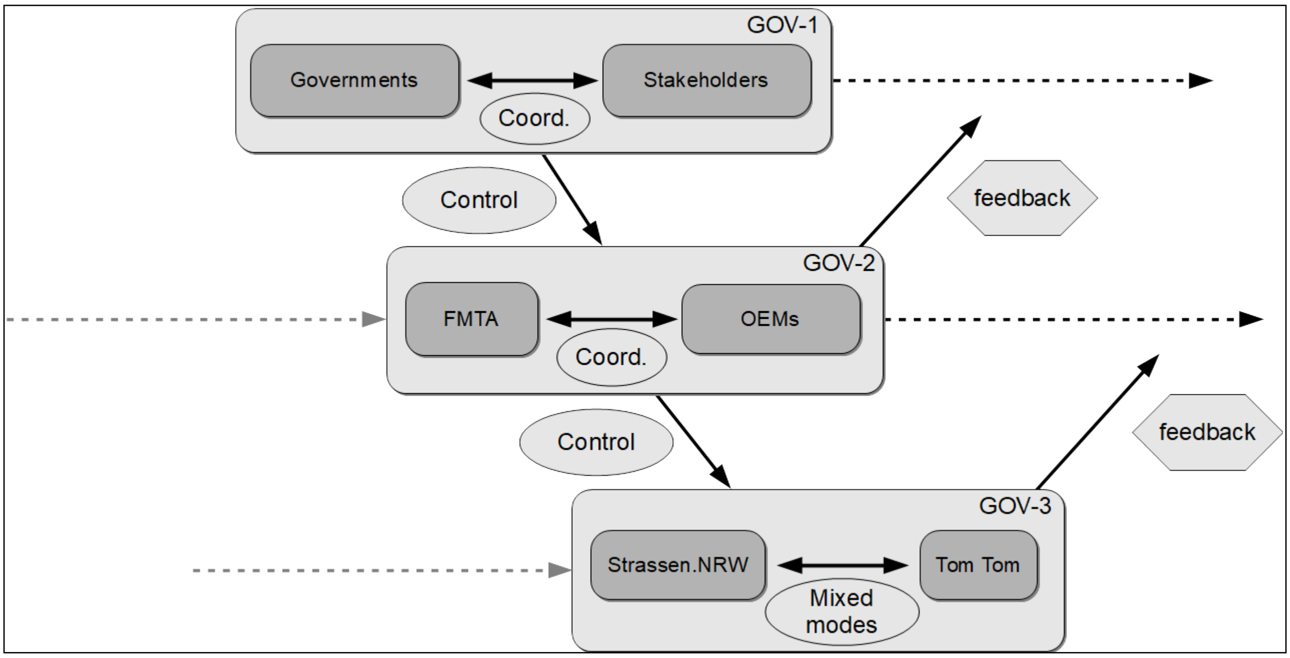

***Fig. 27:** Multi-level governance of traffic (cf. Weyer et al. 2015)*

To include the higher-level governance of the system we use an extended version of this framework (see Fig. 27), where every level of governance follows the logic of the MSE. The traffic system is included at the bottom-level and modelled as the micro-level of this governance system (Weyer et al. 2015). As seen at the bottom-level, private traffic service providers interact with local public authorities and directly affect the traffic. This level is influenced by rules and norms that are decided upon at the middle-level, which is in turn influenced by the top-level, where the government and potential stakeholders shape the path taken by mobility in the long term. For example, the government on the top-level aims to restructure traffic towards more sustainability to meet the demands of stakeholders (the public). On GOV-1 negotiation processes between the government and stakeholders take place in which a concept of the possible changes is established and necessary measures are identified. This concept is then transferred to the level below via control mechanisms. On GOV-2 the Federal Motor Transport Authority (FMTA) interacts with industry actors (e.g. OEMs) to develop subject-specific guidelines and norms. Through these norms control is then exerted on GOV-3, where corresponding institutions are established in order to manage everyday service. Therefore, GOV-1 is the conceptual level, while on GOV-2 this concept is adjusted to the actual circumstances and GOV-3 is the operational level.

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2.2 Real-Time

In future, the governance of transportation will be even more dependent on data transmitted in real-time to cope with the rising volume of traffic. In this context, real-time means that the behaviour of the system depends not only on collecting accurate data but also on its timely processing (Kopetz 2011). A real-time governance of traffic, therefore, requires reliable data sources and efficient algorithms to exploit traffic management opportunities.

2.3 Agent-based modelling and simulation

The traffic sector is a perfect example of a complex system. Many heterogeneous actors influence the system status. Their individual actions aggregate to socially undesirable effects such as congestions and emissions. Furthermore, control over this system is exercised by many actors on many levels.

With computer simulation in general and agent-based modelling and simulation (ABMS) in particular, the complex reality of a system can be reduced to formalised and simplified rules. In particular, the social interactions among agents, and between agents and the system, can be modelled. In this context an agent is a simulated actor with very simple rules of action and decision making, which nonetheless may lead to very complex emergent outcomes (Kron 2010). Agent-based models allow the analysis of these emergent processes or effects in complex and dynamic structures (Kron 2010). ABMS allows us to consider the choices of a large number of heterogeneous actors. The method also lends itself to the implementation of sociological theories which are highly formalised, e.g. the MSE (Adelt et al. 2014). ABMS is therefore well suited to examine the multi-level governance of the traffic system.

2.3.1 Subjective Expected Utility

The subjective expected utility theory (SEU) is a theory of action which is easily transferable into mathematical equations, making it a great tool to implement individual decision making in a simulation in a simplified way.

It is assumed that an actor acts according to the law where is an objective and is an action. This law does not necessarily mean that the action must lead to the objective, but that the actor has a theory of how the world works and believes that the objective follows

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from performing the action (Esser 2000). Using this law, the basic principle of action used for the subjective expected utility theory is then defined as (Esser 2000). Translating the principle from propositional calculus, this means: If is the objective of an actor and this objective follows from the action, then the actor will choose this action to achieve said objective.

In most cases there may be different objectives and different actions or combinations of actions to achieve them. To explain how an actor chooses between different alternative actions and possible objectives, the alternatives are weighted by their expected utility (Esser 1993b). Equation 1 shows how these weights are calculated:

$$SEU(A_i) = \sum_{j=1}^{n} p_{ij} \cdot U(O_i)$$

The subjective expected utility of an action is weighted according to the valuation of the possible outcomes. Additionally, the outcomes are associated with probabilities describing the actor’s estimation of how likely the outcome is to follow from the action. In the end all alternatives are compared and the one with the highest SEU weight is selected.

In our agent-based model the agents act according to this theory. Agents decide between different technologies (e.g. car, bike or public transport) and different routes. In the context of the MSE, this would be situated on the micro-level where individuals decide and act in a decentralised way. In combination and through interaction with the system or other agents, the simulated actions of the latter aggregate and enable us to study the emerging effects in a traffic network (e.g. how the modal split is constituted when certain factors such as costs or comfort are changed). Taking the broader perspective of the multi-level governance of traffic, the question arises how changes on upper levels, like shifts in politically motivated goals, changes in the regulation of the traffic sector and new technologies for controlling traffic, affect the emerging effects. Different forms of governance will have an influence on the driving parameters of decisions or on how decisions are made. With ABMS, we are able to study the effects in our model and evaluate a range of interventions, which we simulated in various scenarios (see 4.2).

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3 State of Traffic Telematics

The term telematics refers to all the information and communication technologies used in the traffic system. The current state of traffic telematics, as we have identified it, is based on the state of research and technologies as well as on the interviews we conducted, hence it is based on the practices of private and public institutions regarding the traffic sector.

In contrast to in-vehicle telematics like Bluetooth hands-free systems for mobile phones or an emergency brake assist, an examination of the governance of traffic relies on the broader definition of telematics including technologies for measuring and controlling traffic. Measurement technologies can be divided into two groups: fixed installations, of which the induction loop is the most commonly known, and floating car (or phone) data, which can be collected throughout a journey. This distinction also applies to the traffic control technologies. In this case fixed installations include variable traffic signs (for speed or routing) while dynamic route guidance systems can be used by means of in-dash systems (i.e. inside the car), navigation devices or smartphones. While firmly installed telematics are superior to floating car data in terms of precision, the latter provide a better coverage.

All of these technologies are ultimately used to manage traffic. The data can be plotted in the basic diagram of traffic (Haight 1963). It displays the flow-concentration curve with which most important characteristics of traffic are measurable (Gerlough and Huber 1975, p. 55-58). According to the observed densities and speeds the travel times can be calculated, the traffic can be managed, or routing recommendations can be made.

4 Simulation and results

4.1 Interview evaluation

Prior to simulation, we evaluated the guided interviews and focus groups with staff from various stakeholders in the traffic sector such as navigation providers, public transport providers, traffic planners, federal traffic offices and local authorities. The aim of these interviews was to investigate the state of development concerning our postulated mode of real-time governance on the one hand and to gain insights about specific demands and probable next steps in the traffic sector.

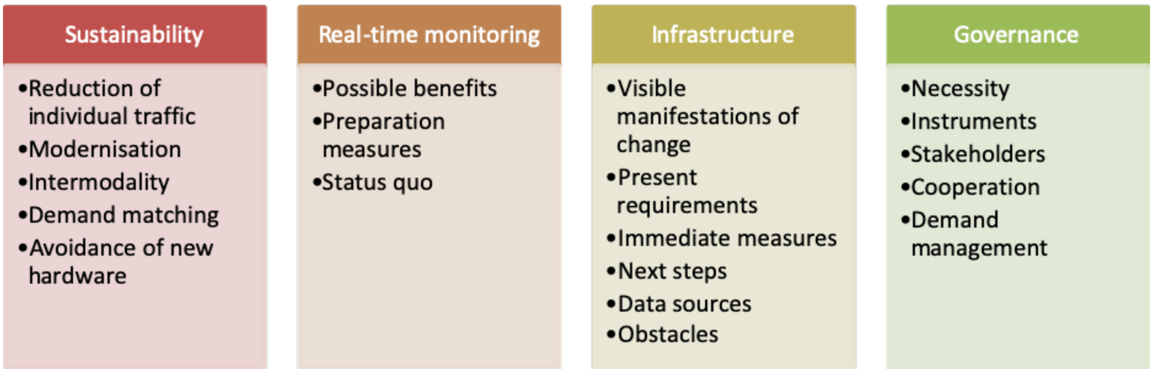

Fig. 28: *Interview categories*

Figure 28 shows the categories and subitems retrieved in the transcripts. It quickly became apparent that, according to our interviewees, future developments in the traffic sector will revolve around the topics of sustainability, real-time monitoring (and influencing) of traffic, infrastructure development and governance.

On the topic of **sustainability**, one of the most frequently mentioned points was a general need for reduction of private vehicles. Furthermore, this should be achieved by optimising existing infrastructure which could lead to an increase in intermodality and efficiency without further investment of resources.

A key technology on this path might be **real-time monitoring** of traffic that allows for an improved prediction of traffic volume in order to use infrastructure more efficiently. During the interviews, it turned out that many steps towards real-time monitoring have already been taken or are currently in progress. Both governmental and economical actors see possible benefits and already have preparation measures in mind that would help to establish real-time monitoring. Additionally, both types of actors expressed willingness to engage in mutual collaboration. This leads to our assumption that real-time governance is a feasible next step. According to our respondents, harmonisation and interchange of traffic data along with an improvement in network technology are vital requirements in order to achieve said goals. In summary, this means that a vast amount of potentially usable data is already being collected while the possibility of processing these data is not yet sufficiently developed.

A similar development is visible in the field of **infrastructure:** While there are already numerous manifestations of change (mostly concerning digitalisation), existing infrastructure needs specific updates to facilitate both real-time governance and

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intermodal transport. According to our interviews, this is currently being complicated by the sheer size of national transport systems such as Germany's, but also by present bureaucratic structures that hamper cooperation between governments and industry. This problem also appears to be accompanied by differences in focus between public and private stakeholders. For instance, private navigation providers clearly prefer software solutions for the collection of traffic data, claiming that there is very little inaccuracy but a large advantage in expense compared to classic hardware-based solutions. This opinion is vehemently opposed by members of the federal traffic agencies, who claim that only hardware sensors are able to provide data in all the required dimensions. Obviously, this dispute is also accompanied by privacy implications that would increase considerably with the use of mobile phone and in-car data for traffic monitoring. This path would then require additional measures to anonymise data, which have yet to be fully developed.

The last topic frequently brought up by our interviewees concerns different options for the **governance** of traffic. While there is a clear consensus about the point that a stronger governance of traffic will be needed in the future, it is not yet clear who the governing institutions will be and what government instruments and modes will be used. Frequently proposed instruments included soft measures such as route recommendations based on current traffic and emission information, incentivisation of certain transport modes or dynamic route pricing. On this topic, the opinions of our respondents largely coincided insofar as bans are not really considered a preferred option by any of the stakeholders. Also, both public and private stakeholders signalled a general willingness to cooperate in the field of traffic governance (even if there is a need to handle political and commercial conflicts of interest in advance of that). This means that, despite both social protagonists wanting to cooperate, they made it clear that they do not want to be fully controlled by the other party. Regarding the group of involved stakeholders, our respondents agreed that there is a chance of new (tech) companies entering the traffic sector that might then also become involved in the process of real-time governance.

4.2 Scenarios

Based on our interviews, to help understand the best course of action, we developed and tested several what-if scenarios. As a comparison we used the base scenario of our simulator, where agents make self-organised and decentralised decisions, and a fixed

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routing scenario where agents that drive follow a fixed route which is calculated beforehand. The two most important scenarios, however, are the *smart navigation* and the *cooperative mode*. In the first, 80 percent of the drivers use a dynamic guidance system with real-time traffic information. This proportion is based on the share of 77 percent of drivers in Germany who already use a navigation device or app (Commerz Finanz 2015). With this scenario we test whether real-time traffic information helps to reach the goals of network efficiency and emission reduction. The second scenario, the cooperative mode, is based on the interviews where public decision-makers and private service providers stated that cooperation is in their mutual interest. Following the results of the interviews, we assumed that the intelligent routing can be used to accomplish both goals. Therefore, it is expanded to include not only real-time traffic information but also real-time emission information. To take into account that neither party wants to be fully controlled, the maximum influence of the emission information is capped at 50 percent, meaning the simulated routing algorithm will be equally based on traffic and emission information.

4.3 The SimCo Simulator

The scenarios are tested with the SimCo simulator, which has already been used for traffic simulations (Adelt and Hoffmann 2017; Adelt et al. 2018). In SimCo, the traffic system is formalised as a network of nodes and edges. Nodes are abstract representations of junctions, homes or workplaces. Edges are abstract representations of streets or bike lanes.

4.3.1 Agents

Agents are the representation of actors in the traffic systems and as such they want to reach certain destinations, represented by the nodes. They travel the model by choosing a route to a node they want to reach and a technology. The set of possible actions an agent may take consists of all combinations of possible routes and technologies that can be used on them e.g.: An agent can use the bike to get to the workplace (Adelt and Hoffmann 2017). The agents decide between these possible actions by utilizing the SEU mechanism.

To represent the heterogeneity of road users, different agent-types are included. Their SEU calculations include preferences like how cheap, fast, eco-friendly and comfortable the alternative is (Adelt et al. 2018). Each type of agent has its own characteristic

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preferences. For example, a convenient agent would prefer comfortable alternatives over eco-friendly alternatives.

4.3.2 Governance

Political instances are not modelled. Governance is instead implemented in the form of scenarios. In each scenario the individual decision making of the agents is influenced in a different way to compare the effects.

4.3.3 Real-Time

For the tested scenarios the real-time information is implemented differently for traffic information and emission information.

In the base scenario agents only have traffic information about the edges that lead to neighbouring nodes. In the smart governance and coordinated mode scenario they have real-time information about the traffic, and therefore the duration of travel, on every edge. The best route to a target node is calculated by the system, considering full information about the system status, so that the agent drives accordingly.

In the coordinated mode the routing algorithm considers an emission factor to calculate the optimal route. The emission factor is based on a rising emission level on an edge. If this level exceeds 60 percent of a limit[1] the emission factor is increased for as long as the emission remains above this level. If emission levels are lower that 60 percent the factor is decreased again. This process happens in real-time. Since the emission factor itself is only changed if certain levels of pollution are reached, it is not based on the real-time status of the system. This leads to a lag in the distribution of emission information that reflects the communication process needed for the coordination.

5 Simulation Results

All four scenarios were run with 6.000 to 12.000 agents to test for the effects of a higher population in the model. To sum up these effects, a higher population resulted in higher emissions and lower network efficiency for all scenarios, although different forms of governance changed the amplitude of the effects. The results shown here are for runs with 12.000 agents only.

1. The limits used are arbitrary numbers suitable for the simulation and not based on emission guidelines.

Figure 29 shows the results for the emissions, the capacity and the agents stuck in traffic. Capacity is a measure for network efficiency. The higher the capacity usage, the better the distribution of traffic, i.e. the network efficiency is higher. The share of agents stuck in traffic is also an indicator for network efficiency. Fewer agents stuck means fewer congestions and indicates a higher network efficiency.

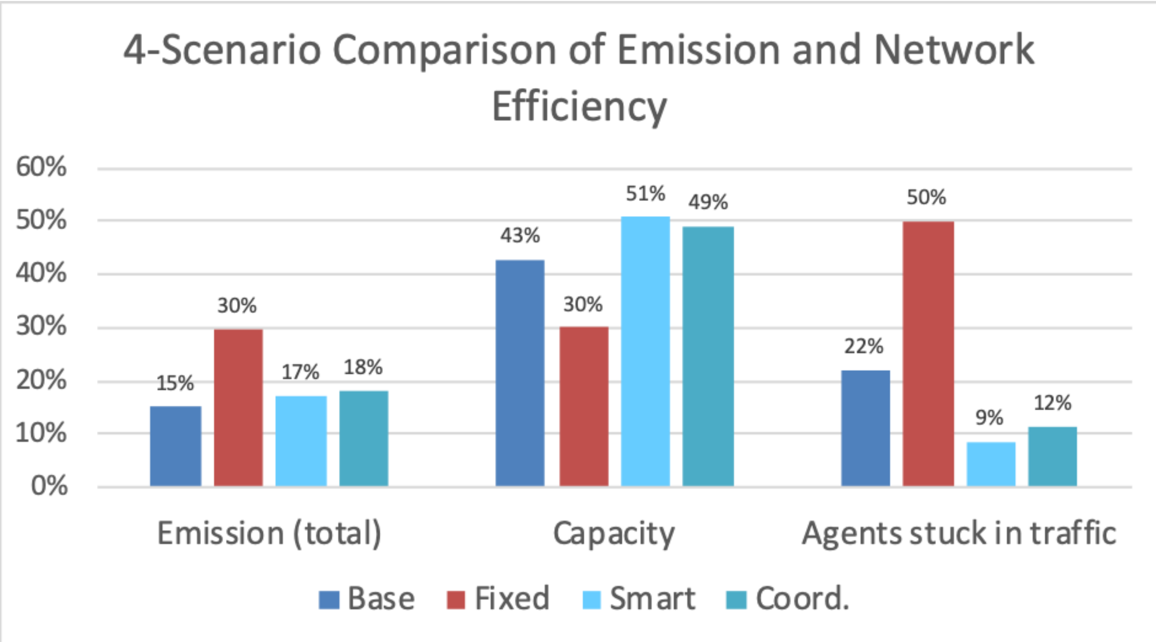

Fig. 29: *Results for emission and network efficiency*

The results show that, compared to the base scenario, fixed routing produces inferior results in every regard. Capacity is lower and more agents are stuck in traffic than in the other scenarios, which shows that network efficiency is low. Also, emission is twice as high as in the base scenario.

For smart routing and the coordinated mode, the results are quite similar. Emission is slightly higher than in the base scenario. The capacity is higher and fewer agents are stuck in traffic, which means network efficiency has increased.

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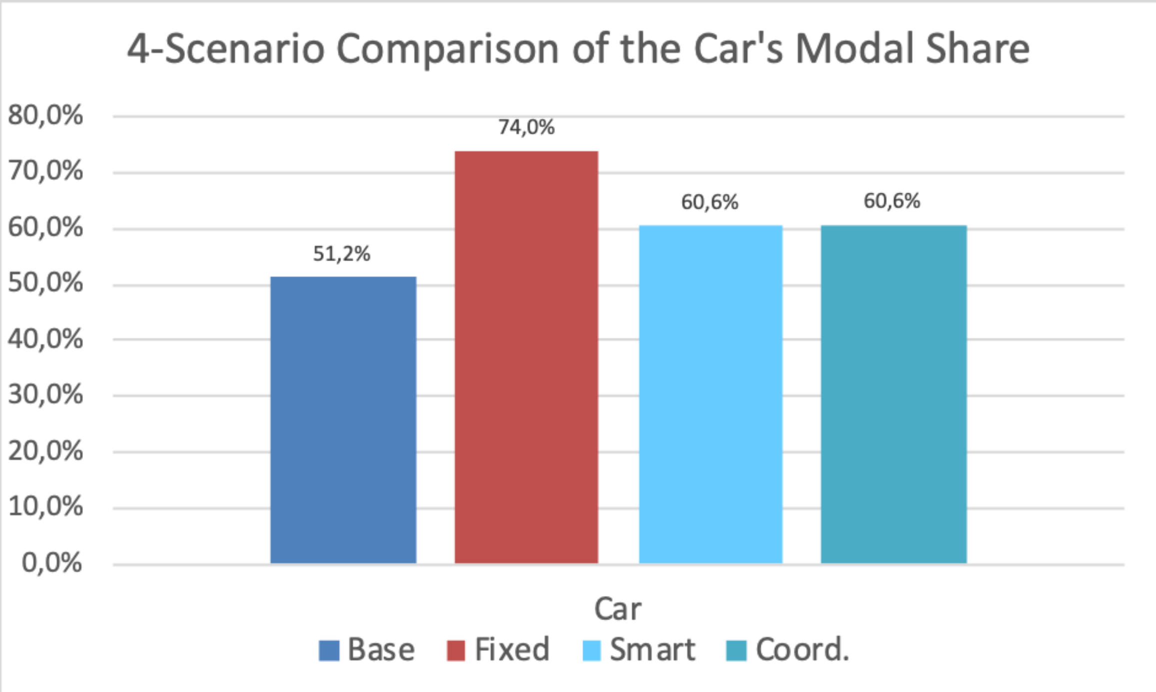

Fig. 30: *Modal Share of the Car*

The share of cars used in the model is depicted in Figure 30. With fixed routes the share of cars is the highest. Again, the smart navigation and coordinated modes show similar results: A roughly 10 percentage points higher usage of cars. These two modes have a higher network efficiency but also a higher usage of cars. This is a result of a typical rebound effect. The higher network efficiency leads to fewer congestions and makes the car more attractive as a mode of transportation. This in turn leads to higher emission. Possible reductions of emission values along with higher network efficiency are impeded by the rebound effect.

Then again, the fixed routing scenario shows a higher percentage of cars in combination with lower network efficiency, which may contradict this trade-off. The very high percentage of agents stuck in traffic may be responsible for this outcome. In the simulation agents can only change their mode of transportation when they reach a home-node, which they are not able to do if stuck in traffic. Therefore, this result is most likely an artefact, caused by the interplay of the governance scenario and the rules of the simulator.

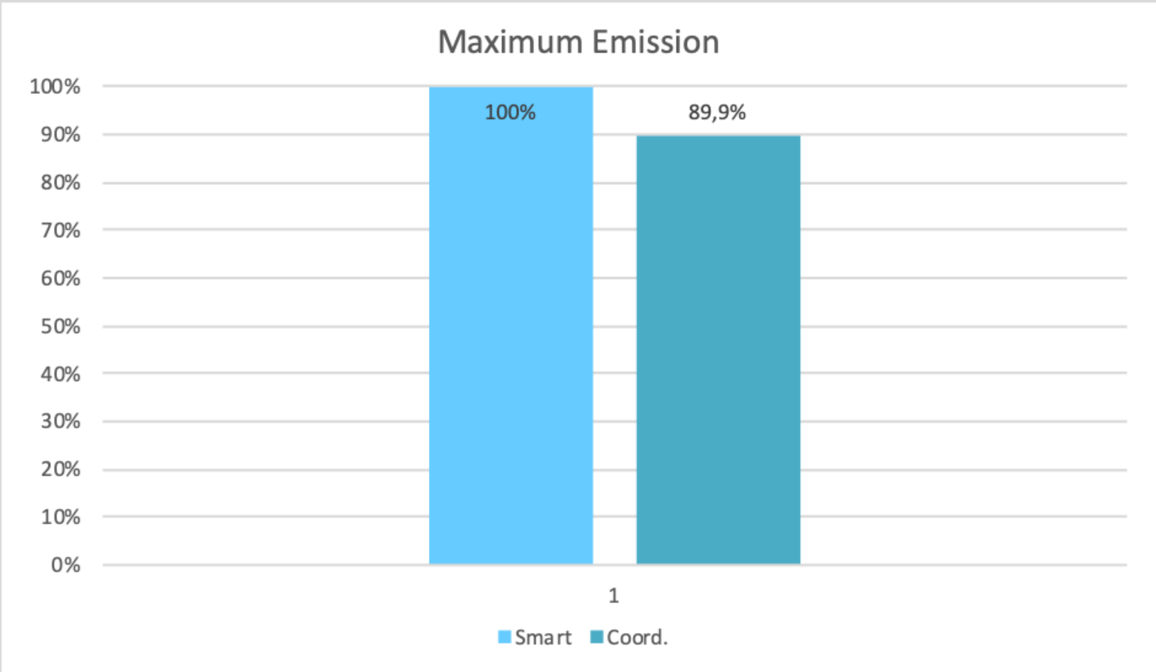

Fig. 31: *Maximum Emission for the Smart Navigation and Coordinated Mode Scenarios*

It is against our expectations that the distribution of emission information in the coordinated mode has no positive effect on emission values. As Figures 29 and 31 show, this is true for the overall emissions, but not for the maximum emissions. Overall emissions are the mean value of emissions of the whole system throughout the whole simulation run. Maximum emissions are the peak value that is reached on the most polluted road during that run. While the reduction of overall emissions is the ecologically more desirable goal, it may also be beneficial to reduce peaks and distribute emissions. This would help to maintain a consistent air quality while relieving busy roads. The coordinated form of governance can help reduce the maximum emissions in the model by roughly 10 percent. Hence, a coordinated mode of governance may help to reach the politically incentivised goal of reducing emission spikes on specific roads, as is mandated by European Union laws.

It is noteworthy that the governance mechanism we installed significantly alters the way the agents move through the system, at least while driving. In the base scenario, agents decide in a self-organised and decentralised way. On every node they can modify their route. With the navigation system in place they must reach a set destination and their route is changed by an algorithm based on the real-time information distributed in the specific scenario. This underlines the fact that the scenarios are what-if scenarios, which

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may not be easily implemented if agents or actors are not willing to comply with routing recommendations. On this topic, we conducted a second study (Cepera et al. 2019), investigating the influence of trust on users' willingness to change their behaviour on the basis of app recommendations. Following Weyer et al. (2018), this second study assumes that trust is a crucial element of a big data process like the real-time governance that we present here. Only with mutual trust between involved actors and technology will the process be stable and users willing to follow algorithmic recommendations. The results of this second study show that dispositional, institutional and interpersonal trust indeed have a significant influence on users' willingness to modify their behaviour. For the special case of navigation apps, we found that 69,6% of drivers are willing to change their route according to an app-based recommendation while driving (cf. Cepera et al. 2019). This shows that real-time governance of traffic, if implemented, would have a high acceptance rate and a great range via app-based recommendations.

6 Conclusion

Using agent-based modelling (ABM), we compared the scenarios with a status quo base scenario prior to comparing them among each other. Our findings show that smart navigation vastly improves traffic flow and the efficiency of an existing road network. Simultaneously, there are negative effects in terms of an increase of car usage. Due to improved traffic flow, road users are incentivised to use their cars more often, since travel times decrease. In this case, social logics of individual decision-making contradict the goal of emission reduction with algorithmic governance alone. On the micro-level of the model, smart routing recommendations lead to better individual goal attainment (in terms of reaching desired destinations) shown by better network efficiency, while reducing individual autonomy when it comes to routing decisions.

When taking emission regulations into account, the coordinated governance mode can decrease maximum emissions. Either way, the overall decrease of emissions that we hoped for does not occur and is accompanied by a decrease of network efficiency, forming a trade-off between emissions and network efficiency that is prevalent in all our findings.

On the one hand, we can show that algorithmic governance can reduce maximum emissions and increase traffic flow but, on the other hand, it fails to satisfy the ambitious politically installed targets. This shows that the examined algorithmic governance can only be used to its full potential if there is a simultaneous shift in societal prioritisation of different modes of transportation. Assuming that the attainment of political objectives is a condition for the legitimacy of this form of algorithmic governance, our simulation shows that algorithmic governance is indeed an adequate tool. However, societal phenomena (like increased car usage) may contradict these efforts. This shows a need for the incorporation of emergent social effects in the governance mechanism itself.

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