SIMULATION STUDY ON THE EFFECTS OF AN EMISSION-BASED DYNAMIC FREEWAY CONTROL

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ABSTRACT
Dynamic freeway control systems (FCS) aim to improve traffic safety and optimize vehicle flow on highly frequented freeway segments. This study considers emissions as an additional control objective. Various emission-based variable speed limit strategies and truck overtaking regulations are evaluated to mitigate air pollution resulting from traffic. To quantify the effects of an emission-based FCS, a microscopic traffic flow model of a section of freeway A5 near Frankfurt, Germany, equipped with an FCS use. The conventional control algorithm is extended by integrating emission-based control programs into the model. The results show that emission reductions can be primarily attributed to two factors: first, the reduction in speeds, and second, the alleviation of congestion through stricter traffic harmonization. The study finds that the most significant potential for emission reductions occurs during periods of medium traffic flow rates, leading to a NOx reduction of up to 10% and a CO2 reduction of up to 6%.

Keywords: emissions, dynamic freeway control system, microscopic traffic flow simulation, German freeway

INTRODUCTION

Dynamic freeway control systems (FCS) are installed on heavily frequented freeways to enhance road safety and optimize traffic flow. FCS monitor traffic conditions and automatically determine speed limits, overtaking restrictions, and warnings, which are then displayed on variable message signs along the freeway. On freeways equipped with FCS, detectors collect traffic data that contain a potential for further development of the control algorithm. In this study, we investigate the reduction of traffic-related air pollution by adapting the control algorithm, which represents an approach that has not yet been fully exploited.

The environmental effects of local air pollutants are influenced by the dispersion and chemical conversion of emissions in the atmosphere. These processes, in turn, are affected by meteorological factors, such as wind, rain, and temperature distribution across different atmospheric layers (*1, 2*). Managing these external factors is challenging, and measuring immissions, i.e., the concentration of pollutants in the air, requires extensive and resource-intensive methods. However, FCS have a direct impact on emissions, i.e., the release of pollutants by vehicles, by modifying traffic conditions.

The extent of achievable emission reduction is influenced by various factors, including vehicle speeds, driving dynamics affected by traffic conditions and road characteristics, traffic composition (such as heavy-duty vehicles and the age and composition of the fleet), as well as ambient temperature (*3, 4*). Vehicle speed significantly impacts emission levels, indicating that traffic control measures emphasizing speed reduction can effectively contribute to emission reductions (see Section 3.3). In this context, conventional FCS already positively influence traffic emissions by harmonizing traffic flow, consequently reducing high speeds and accelerations.

Within the scope of this study, we demonstrate that these positive effects of a conventional FCS on air pollution can be further increased by adding supplementary control criteria. As emissions can be calculated from the traffic data already collected by the FCS using emission models, a shift towards an emission-based traffic control holds significant potential. The present study examines the impact of emission-based algorithms of FCS on traffic flow, travel times, and the reduction of air pollutants. Therefore emission-based control programs related to speed and truck overtaking restrictions are evaluated in different traffic situations using a microscopic traffic flow model. The model is equipped with a compliance model reflecting the road users' reactions to the control measures.

PRELIMINARIES AND LITERATURE REVIEW

Dynamic freeway control systems (FCS)

The main objective of FCS is to enhance traffic safety by incorporating hazard warnings within the FCS area, such as alerts for accidents or construction zones. Another goal is to achieve traffic harmonization, leading to optimized traffic flow and a reduced probability of traffic collapses. Harmonizing traffic flow also reduces the risk of accidents and mitigating the environmental impact caused by traffic. In 2015, approximately 2,300 kilometers of German freeways, representing 8.8% of the total German freeway network, were equipped with an FCS (*5*). Moreover, FCS and comparable traffic control systems are implemented in other countries as well. Generally, these deployed systems share similar control objectives, system structures, and control models as those in Germany.

In this study, we utilize a microscopic traffic flow model of a section of freeway A5 near Frankfurt am Main, Germany, equipped with an FCS. Understanding and evaluating the functionality of the FCS under investigation requires consideration of some key characteristics of German freeway traffic. Firstly, it is important to note that there is no general speed limit for passenger cars on German freeways, while trucks are subjected to a speed limit of 80 km/h. This leads to significant variations in driving speeds depending on the traffic situation, resulting in traffic disruptions. To address this issue, FCS implement harmonization programs, such as establishing a uniform speed limit of 120 km/h. Furthermore, in Germany, driving on the right is mandatory, leading to a pattern where fast-moving vehicles use the left lanes for overtaking while slower vehicles stay on the right lanes. Consequently, there is a speed gradient from left to right. Driving speeds are heavily influenced by lane choices, encouraging frequent lane changes. Trucks primarily stay on the right lanes and rarely overtake.

The main control programs implemented within the control algorithm of an FCS include speed harmonization programs, truck overtaking bans, and various warnings concerning traffic congestions, adverse weather conditions, or upcoming construction sites. An additional measure to increase the capacity of a freeway section is a temporary hard shoulder running. During periods of capacity constraints, the hard shoulder can be opened for traffic, providing an additional lane without the need for infrastructure expansion.

An FCS is composed of detector stations for collecting traffic data, as well as display gantries on which dynamic traffic signs are displayed. Often, these detector stations and display gantries are co-located. In Germany, FCS operate based on the control algorithms outlined in the German guideline MARZ (*6, 7*). The German state of Hesse has further developed this MARZ algorithm into a more specialized algorithm based on traffic data from individual traffic lanes. The FCS operates on a one-minute control interval. The control loop starts with analyzing traffic and environmental conditions to determine the current traffic situation. When the conditions for activation or deactivation are met, the FCS generates switching requests for the corresponding control programs. Some control programs include additional switching delays. This means the switching request is only generated if the activation criteria have been continuously met for a specific duration. Similarly, there are minimum durations for some control programs before a deactivation request is generated, ensuring that the control actions are consistently displayed for a certain period. Multiple control programs, such as traffic jam warnings and harmonization, can simultaneously generate switching requests for a single display gantry. Subsequently, all switching requests for a display gantry are prioritized, with the most restrictive control request typically given priority. Subsequently, the remaining switching requests are coordinated longitudinally and laterally. Longitudinal coordination ensures consistent displays on successive display gantries. Meanwhile, lateral coordination adjusts the displays of different lanes within a single display gantry. Finally, the selected traffic signs are displayed on the gantries, and drivers respond to the information provided.

Numerous studies have examined the effects of FCS on traffic flow. The harmonizing impact of dynamic speed limits has been well-established (*8–12*). Similarly, studies have demonstrated enhanced traffic flow stability with increased speed levels at high traffic volumes (*9, 11, 13*). However, the impact of FCS on freeway capacity remains unclear. While some studies suggest that implementing FCS can result in increased capacity (*14, 15*), others conclude that no capacity increase can be achieved (*9, 11*). Papageorgiou et al. (*16*) showed that dynamic speed limits lead to a reduction in traffic flow at low occupancy levels but an increase in traffic flow at high occupancy levels. The most significant effect on traffic flow is achieved with a speed limit of 50 mph (approximately 80 km/h). A speed limit of 60 mph (approximately 97 km/h) shows almost no difference compared to the uncontrolled state.

Regarding the truck overtaking ban (TOB), the findings from various studies are inconclusive. Studies have found that implementing TOB on two-lane freeways with traffic volumes exceeding 2,000 vehicles per hour on flat terrain can be beneficial (*17, 18*). Moreover, Brilon and Drews (*19*) demonstrated travel time benefits for passenger cars, particularly on uphill sections. In general, dynamic, or at least time-dependent TOB adapted to local conditions are recommended (*19–21*). A study by Hoogendoorn and Bovy (*22*) showed mixed results on traffic flow. Separating vehicle types through TOB generally resulted in higher capacity in non-congested states. Conversely, in traffic states with high traffic volumes, TOB were shown to potentially contribute to the formation of traffic congestion.

Emission modeling

A recognized macroscopic approach used as a European standard to estimate emissions of road traffic is the emission model of the Handbook of Emission Factors for Road Traffic (HBEFA) (*23*). It is based on emission factors that show fuel consumption and emissions rates per vehicle kilometer as a function of vehicle class, travel speed, and traffic conditions. In addition, the composition of the vehicle fleet is considered concerning the various exhaust emission standards (Euro classes) and drive types (gasoline, diesel, electric, hybrid-electric). Thus, the consideration of environmental impacts is always related to a specific year and country (Germany, France, Sweden, Norway, Switzerland, or Austria). The HBEFA distinguishes between the traffic conditions fluid, dense, saturated, stop+go, and stop+go2. These traffic conditions are described qualitatively; speed reference values are given depending on road type and speed limit.

The approach of HBEFA's emission factors is comparable to the calculation type "emissions rate" of the Motor Vehicle Emission Simulator (MOVES), the emission model distributed by the U.S. Environmental Protection Agency (*24*). The complete emission inventory must be calculated by multiplying the emission rates by the number of vehicles and the driven distance. If spatially continuous data on a single vehicle level are available for emission calculation, microscopic approaches such as the emission model PHEMlight can be used (*25*).

Emission reduction measures can also be analyzed by using traffic simulations. In this case, microscopic emission models require realistic microscopic driving behavior. The driving dynamics, particularly the acceleration behavior, must be calibrated concisely (*26, 27*). For evaluating the effect of variable speed limits on emissions the use of microscopic traffic flow simulations is recommended (*28*).

Emission reduction potentials of FCS

Speed limits are the usual traffic control measurements to reduce freeway emissions, additionally to ramp metering. The effect of truck overtaking bans on emissions was found to be insignificant (*19, 29*).

Van Benthem (*30*) examined the impact of large-scale speed limit increases in the United States in 1987 and 1996. The study finds that a 10 mph speed limit increase leads to 8-15% more nitrogen oxide (NOx). Estimating the total social costs, including travel time losses and raises in accident rate, the paper concludes that the optimal speed limit should be around 55 mph (approx. 90 km/h). To move closer to an optimal speed taxation approach, the study suggests implementing flexible speed limits that vary based on time-of-day and road conditions.

In some countries, traffic control measures that explicitly aim to reduce air pollution are already implemented. Mainly static speed limits are used, i.e., in the Netherlands (*31, 32*). There the reduction potential ranged from a 5% to 30% reduction for NOx and 5% to 25% for particulate matter (PM) for speed limits of 80km/h. In Austria, several immission-based speed limits are in place. One example is the FCS in the greater Graz area which reduces the maximum permissible speed to 100 km/h based on immission levels. The switching states of the system are determined by measured air quality, traffic data, and weather models (*33*). An evaluation for 2021 revealed a reduction of 9.0% of NOx emissions, 6.9% of PM emissions, and 4.4% of carbon dioxide (CO2) emissions from passenger cars (*34*). In the area of Innsbruck, a traffic and immission-based speed control system was implemented in 2007. This FCS limited the maximum allowed speed to 100 km/h when there were increased air pollutant levels. In 2014, a static speed limit replaced the immission-based speed restriction. An evaluation for different road sections revealed that the annual average concentration of NOx was reduced by 8.6-17.5% with variable speed limits and by 14.6-20.0% with the static speed limit compared to unregulated traffic with a regular Austrian speed limit of 130km/h (*35*).

There are also studies on variable speed limit schemes which do not explicitly intend to reduce emissions (*15, 36*). Further research investigated the potential of emission reductions through variable speed limits using traffic and emission models (*37–39*). Incorporating connected vehicles for advanced speed limit schemes can improve traffic parameters, energy consumption, and emissions reduction (*40, 41*).

When summarizing studies evaluating the effect of speed limits on freeways, the reduction potential can be estimated at approximately 5 - 10% on NOx emissions, slightly lower for PM, and up to 5% on CO2 emissions. Depending on the value attributed to emissions and travel time, this might raise the overall economic benefit (*30, 37*). While there is a considerable amount of literature on the effect of speed restrictions on emissions, there is a lack of studies explicitly focusing on emission-based traffic control on freeways. A further distinctive aspect of this study lies in exploring algorithms using FCS rather than static speed limits.

METHODS

Subject of investigation

In this study, we use an existing traffic flow model that covers a 30-kilometer section of the freeway A5 near Frankfurt am Main, Germany. With a maximum daily traffic volume of approximately 160,000 to 200,000 vehicles per day in 2019, the A5 near Frankfurt represents one of Germany's most heavily frequented freeway sections. The section under investigation includes one junction (AS 16) and three freeway interchanges (AK 17, AK 18, AK 19). Both directions of travel are taken into account in the analysis.

The section is equipped with an FCS, consisting of 35 detector stations and display gantries in the northbound direction and 34 in the southbound direction, referred to as cross-sections in the following. The main line of the freeway is composed of three lanes per direction of travel and a temporary hard shoulder running is operated between AS 16 and AK 18.

Real detector and display data from the FCS are employed to test and evaluate the emission-based control algorithm. The detector data provide traffic volume and average speed per lane and individual records for cars and trucks in one-minute intervals. The dataset covers a period of 1.5 years in 2019 and 2020. We chose September 18, 2019, as a representative day for testing emission-based control algorithms.

Additional data sources such as Floating Car Data, typical diurnal profiles, and individual vehicle data were used to calibrate and validate the microscopic traffic model.

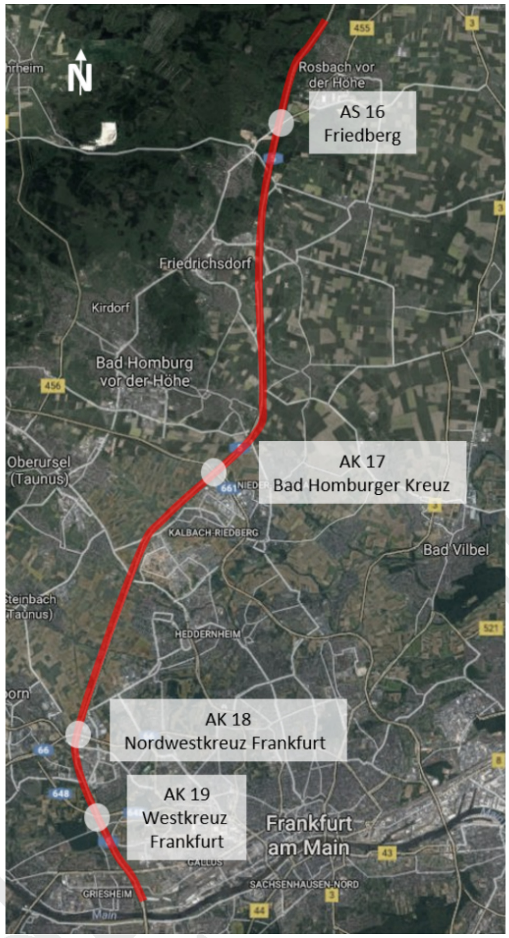

FIGURE 1 Overview of the modeled section of the freeway A5

Modeling an FCS

To illustrate the impact of the FCS in a microscopic traffic flow model, three components are required: a traffic flow simulation, an implementation of the FCS control logic, and a compliance model. The traffic flow model employed in this study includes all three components. The model represents a further development from the one described by Weyland et al. (*42*). The software tool PTV Vissim was utilized for the modeling process. The model incorporates analyses on traffic composition, traffic flow, lane distribution, headways, and origin-destination relationships along the section. Furthermore, an algorithm was developed to simulate the temporary hard shoulder running, replicating the manual control operations carried out in real-world.

The second component includes an implementation of the FCS control algorithm in Python code and its pairing to the Vissim model through its COM interface. The algorithm's parameters and threshold values were validated using field data from the detector stations and display data from the FCS. At each detector station of the real FCS a data collection measurement is created in PTV Vissim. In the simulation, these data collection measurements record traffic data necessary for the control algorithm. To simulate the drivers' reaction to the dynamic traffic signs, desired speed decisions are added at each of these data collection measurements in the model. When the control algorithm sets a new speed limit for one or more data collection measurements, the corresponding desired speed distribution, determined from the compliance model, is assigned to the desired speed decisions. Vehicles crossing a desired speed decision receive a new desired speed from the corresponding distribution.

Lastly, a compliance model that represents the response of road users to the dynamic displays of the FCS is implemented. A simulation in which all vehicles adjust their speed to the speed limits, all trucks adhere to the overtaking restrictions, and the hard shoulder lane is fully accepted as a regular lane would not yield realistic results. These aspects were examined based on traffic data leading to the development of a compliance model that reflects realistic compliance and can be used to simulate the effects of the freeway control system. Desired speed distributions were determined using the Kaplan-Meier estimation procedure (*43*). Those distributions vary for different vehicle classes.

The traffic flow model, control model, and compliance model were then combined. The result is a traffic flow model that realistically represents the traffic situation on a heavily frequented German freeway, including freeway control measures and the reactions of road users on a typical workday. Such a model enables the simulation-based examination of traffic control measures before their actual implementation. Especially the modeling of road users' reactions to dynamic FCS displays in a microscopic traffic flow simulation represents a relatively unexplored area of research so far. Based on this setting, an emission model can be included as an additional component that makes switching requests based on an emission calculation. Figure 2 gives an overview of all these components, illustrating one control loop of the system.

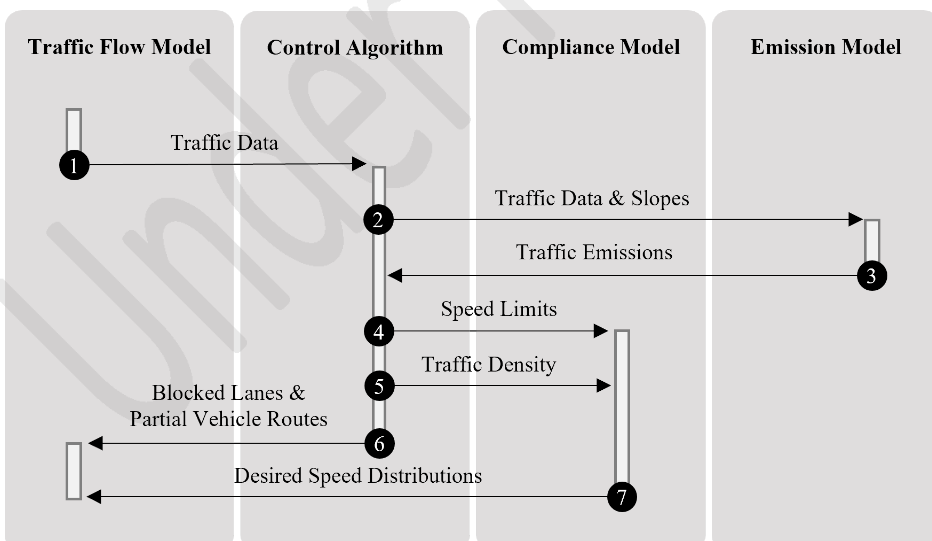

FIGURE 2 Components of an emission-based FCS

Emission calculation

We utilized the Handbook of Emission Factors (HBEFA 4.2) to calculate emissions. The emissions were determined using aggregated traffic data collected by the FCS at local detector stations. In order to facilitate real-time application, the calculations were conducted solely on a macroscopic level not being dependent on the availability of individual vehicle trajectories. To calculate emission factors per vehicle kilometer for each cross-section of the study route, we considered the longitudinal inclination. We scaled the emission factors to the section length for total emissions. The data basis for this calculation consisted of minute-by-minute detector data, which provided traffic volume and speeds categorized by vehicle type (passenger cars and trucks). We used the fleet composition of 2022 stored in the HBEFA. The traffic conditions "fluid", "dense", "saturated", "stop+go", and "stop+go2" were differentiated based on speed thresholds. Emission factors were determined for four vehicle categories: passenger cars, light-duty vehicles (LDVs), heavy-duty vehicles (HDVs), and coaches. We assumed that LDVs accounted for 10% of the traffic volume of passenger cars and coaches accounted for 2% of the traffic volume of HDVs based on the evaluation of individual vehicle data. We considered NOx and PM from exhaust gases as pollutant components due to their adverse effects on human health and the existence of recommendations and legal requirements for limit values. Additionally, we calculated CO2 emissions as a critical greenhouse gas. The emission programs regulate velocity or overtaking based on NOx emission values. Since the emissions strongly depend on traffic volume, other relevant exhaust emission components, such as PM emissions, exhibit a similar trend. We selected the default threshold values for NOx as follows:

- Switching-on criterion: 32g/min
- Switching-off criterion: 28g/min

A sensitivity analysis demonstrated the significant influence of threshold values choice. This suggests that calibration of the thresholds specific to environmental conditions, possibly on each detector station, may be necessary. Moreover, variability due to ambient temperature should be taken into account. Season-dependent threshold values could improve the precision of the control.

Dynamic emission programs

We have developed multiple emission-based programs that deviate from the conventional control programs through two distinct modifications: more restrictive speed reduction and alteration of the truck overtaking ban. All of these programs utilize predefined emission thresholds for NOx (see chapter 4.3) as the criterion for activation. The emission-based programs evaluate the traffic situation and the pollution load each minute. They are integrated into the prioritization process and the lengthwise and crosswise adjustment in the same way as the conventional programs are. To evaluate the emission-based control programs, we compared them to the reference scenario, which represents the conventional control algorithm with no modifications, while maintaining the same initial traffic conditions, i.e., simulation time and input traffic volumes and speeds.

Two primary approaches are employed in the design of speed control programs. The first approach involves imposing a speed limit when exceeding the emission threshold. We tested speeds of 80, 100, and 120 km/h and named the corresponding programs "T80", "T100", and "T120", respectively, with "T" denoting "tempo". The switch is activated at the demanding cross-section and the subsequent cross-section. For speeds of 80 and 100 km/h, a speed limit of 120 km/h is displayed at the previous upstream cross-section to adjust the speed gradually. There is a 5-minute delay for activation and a 20-minute delay for deactivation. For the T120 program, an additional platoon tracking method is implemented to enhance effectiveness with minimal traffic intervention. The concept involves tracking a platoon over an extended period and applying speed limits only to platoons with high emissions.

The second approach for speed reduction programs involves enhancing the existing speed harmonization programs in the event of high emissions, designated as "H" for harmonization. The speed reductions to 80, 100, or 120 km/h are activated earlier and deactivated later. This entails introducing a factor that reduces the thresholds for activating harmonization measures based on traffic conditions. When emissions are exceeded, this factor is set to 0.85. Similar factors are already utilized in traffic control to account for unfavorable conditions such as darkness or rain.

TABLE 1 Overview of emission-based speed reduction programs

Program Abbreviation	Short description
T80	Speed limit reduction to 80 km/h, when exceeding the emission threshold value
T100	Speed limit reduction to 100 km/h, when exceeding the emission threshold value
T120	Speed limit reduction to 120 km/h, when exceeding the emission threshold value
T120 Platoon	Speed limit reduction to 120 km/h, when exceeding the emission threshold value with platoon tracking
H	Intensification of the harmonization programs with reduction factor 0.85

Speed programs are realized in the simulation by adapting the desired speed distribution of the vehicles according to the compliance model, see Section 4.2. An overview of the new emission programs is presented in Table 1. The distinctive control behavior of these programs is most evident under high traffic volumes. Figure 3 illustrates the displayed speed limits of the programs for the southbound direction during morning peak hours in a distance-time diagram.

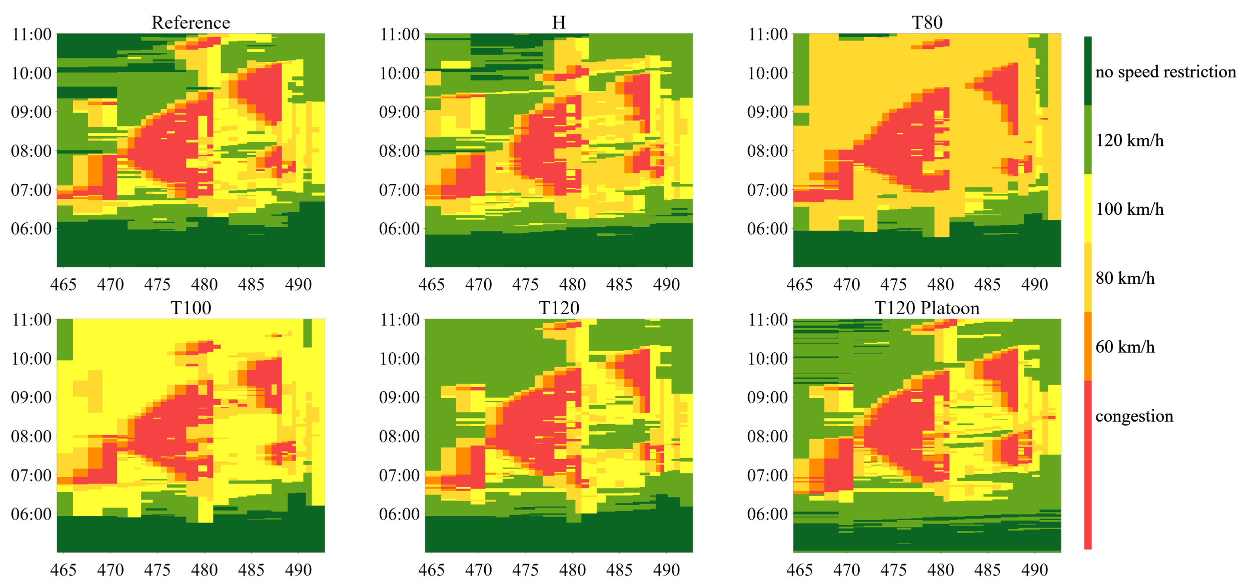

FIGURE 3 Distance-time diagram of displayed speed limits of the different emission-based speed control programs (southbound direction)

The distance indicated on the x-axis uses the official mileage in km of the modeled highway section. The reference scenario, displayed in the upper left corner, demonstrates increasingly restrictive control measures as traffic volume rises. Two waves of congestion are identifiable (highlighted in red). As expected, the programs T80, T100, and T120 exhibit a high prevalence of the respective speed limits 80, 100, and 120 km/h. The T120 Platoon program shows distinctive lines representing speed limits of 120 km/h, generated through the platoon tracking approach.

Another modification to the conventional control involves the reinforcement and relaxation of the truck overtaking ban. Similar to the speed program of intensification of the harmonization, a factor is activated during high emissions to facilitate or hinder the activation of the truck overtaking ban. The factors 0.85 and 1.15 were selected for strengthening and relaxation, respectively. Additionally, a suspension of the truck overtaking ban is being tested. If the emission threshold value is exceeded, the truck overtaking ban is lifted, allowing trucks to overtake other vehicles.

Evaluation method

Two specific time periods were selected to assess the emission programs' performance in different traffic conditions. The first period encompasses the morning peak hours from 5 a.m. to 11 a.m., while the second period covers the midday hours from 11 a.m. to 3 p.m of September 18th. Both periods were considered for both driving directions, resulting in four distinct traffic situations. These situations are depicted in Figure 4, illustrating the traffic volumes in a distance-time diagram. High traffic volumes are observed during the morning peak hours in the southbound direction, with at least two congestion waves being identifiable. In the northbound direction, traffic volumes are relatively low in the morning, while medium traffic volumes are present during the midday period for both driving directions. The figure also highlights the changes in traffic volumes at cross-sections with entry and exit points to the freeway, as previously described in Section 4.1.

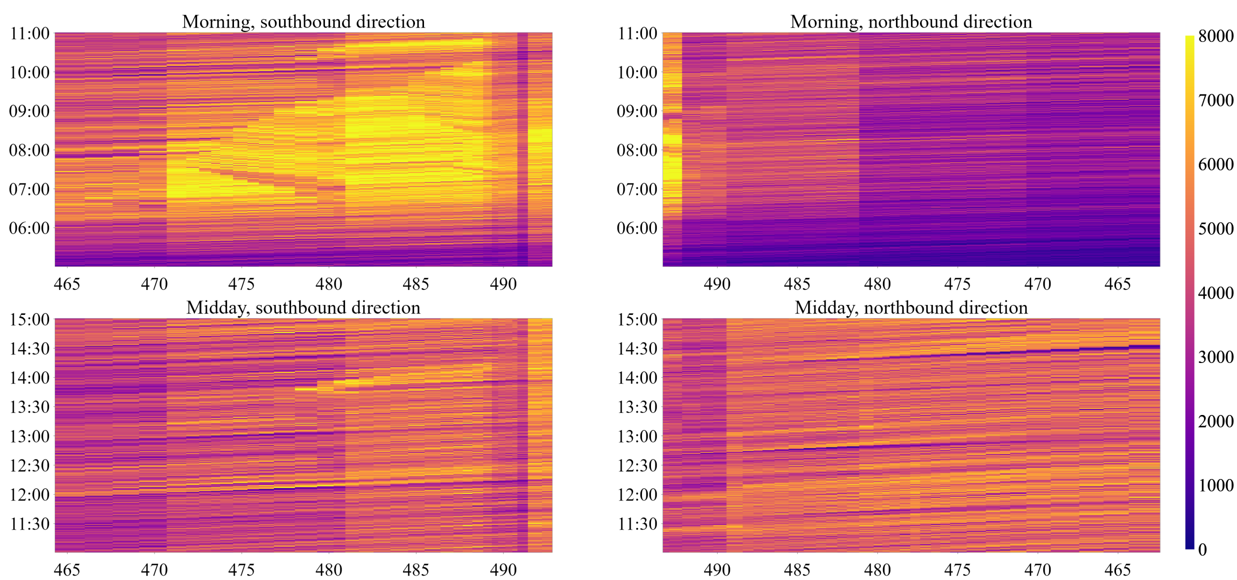

FIGURE 4 Considered traffic situations in terms of traffic volume

The number of simulation runs was determined to achieve a significance level of 95% and a confidence interval of 1% for relative emission component reductions and 2% for changes in travel time. At least five simulation runs were performed, while ten runs were conducted in most cases.

The control programs were evaluated based on their effectiveness in reducing the pollutant components NOx, PM, and CO2 and their impact on travel time. Travel times were calculated as mean travel times averaged over simulation time and the modeled freeway section. Additionally, we compared the mean travel time to the summed travel time of all vehicles. A summed travel time is necessary to quantify the overall travel time loss for the whole collective of road users. It considers how many vehicles are affected by a change in travel time. This could be further used when monetizing travel times to calculate economic costs.

Several other values were evaluated to gain further insight into the emission programs' behavior. The switching duration is the relative time when a signal is displayed, which was triggered by an emissions program. Even though emissions might be high, the switching duration of an emission program could be low, due to prioritized conventional programs. Lastly, the actual relative times when a displayed signal shows 80, 100, or 120, regardless of the triggering program, are evaluated. The switching duration and display signal times are expressed in (relative) minutes, multiplied by the travel distance for which they are intended. For example, a switching duration of one minute signifies a display's activation over one kilometer for one minute. Therefore, these variables are evaluated both temporally, concerning the total time, and spatially, with respect to the affected distance in relation to the total distance.

RESULTS AND DISCUSSION

This section discusses the impact of emission-based programs of an FCS on traffic flow and emission reduction. It evaluates speed reduction and truck overtaking ban programs separately. Effects of a combination of them could be a potential topic for future research.

Effects of speed control programs

Table 2 gives an overview of the results regarding the changes in travel time and emissions for the speed reduction programs.

In general, the results demonstrate that higher emission reduction potential is achieved with more restrictive speed limits, particularly with the T80 and T100 programs. Accordingly, these programs also impact travel times, whereas the changes in travel time observed for T120 are negligible.

During periods of medium traffic volumes, as at midday, there is considerable potential for emission reduction with relatively low travel time losses, especially with the T80 and T100 programs. The switching duration for these programs is approximately 50% in the southbound direction and around 30% in the northbound direction. Conversely, during off-peak hours in the morning in the northbound direction, the switching duration is below 10%, resulting in minimal effects on travel time and only slight emission reduction.

Considering its chosen parameters (such as the emission threshold of NOx and the reduction factor of 0.85), the impact of program H seems limited. Its potential influence is more pronounced during peak-hour periods since harmonization programs are more frequently employed during those times. A sensitivity analysis concerning the reduction factor revealed that a minimum value of 0.85 is recommended. However, it is possible to consider further tightening, especially when prioritizing the reduction of emissions.

When comparing the T120 Platoon program, which incorporated platoon tracking into the T120 program, there is little change observed in travel time. However, an improvement in emission reduction is evident across all four traffic situations. However, the reduction rates remain

TABLE 2 Results of emission-based speed control programs

Driving direction south; 5 a.m. - 11 a.m.

Emission Program	Increase in travel time [%]	NOx reduction [%]	PM reduction [%]	CO2 reduction [%]
T80	3.7	7.0	5.4	4.0
T100	2.1	4.0	4.2	2.0
T120	0.1	0.2	0.4	0.0
T120 Platoon	-0.1	0.4	0.6	0.1
H	1.1	1.9	1.5	1.1

Driving direction south; 11 a.m. - 3 p.m.

Emission Program	Increase in travel time [%]	NOx reduction [%]	PM reduction [%]	CO2 reduction [%]
T80	2.0	10.4	9.5	6.2
T100	2.5	7.1	7.6	3.4
T120	-0.8	2.3	2.9	0.9
T120 Platoon	-0.1	2.8	3.4	1.2
H	0.5	1.3	1.4	0.7

Driving direction north; 5 a.m. - 11 a.m.

Emission Program	Increase in travel time [%]	NOx reduction [%]	PM reduction [%]	CO2 reduction [%]
T80	0.5	3.3	3.0	1.7
T100	0.3	2.7	2.8	1.2
T120	-0.5	0.9	1.0	0.4
T120 Platoon	-0.2	1.5	1.9	0.6
H	-0.2	0.9	0.9	0.5

Driving direction north; 11 a.m. - 3 p.m.

Emission Program	Increase in travel time [%]	NOx reduction [%]	PM reduction [%]	CO2 reduction [%]
T80	3.2	8.5	7.0	4.3
T100	2.2	6.1	6.0	2.8
T120	0.1	0.8	1.0	0.4
T120 Platoon	0.0	1.2	1.4	0.4
H	0.7	1.8	1.7	1.1

relatively low and are primarily due to longer switching times, rather than achieving greater efficiency through targeted intervention.

In all speed reduction programs, increases in travel times are mainly distributed evenly between passenger cars and trucks. However, the majority of emission reduction is contributed by passenger cars.

Effects of programs modifying the truck overtaking ban

The impact of reinforcement and relaxation on the truck overtaking ban depends heavily on the initial use of this regulation. In the northbound direction, the switching duration of the truck overtaking ban was increased from around 14.2% to approximately 19.0% during reinforcement and lowered to around 10.6% during relaxation. In the southbound direction, the changes in the control displays were less significant, with rates of 69.5% for the reference, 70.9% for reinforcement, and 68.4% for relaxation. However, the overall effects on travel time and emission reduction were minor. Both relaxation and reinforcement resulted in less than 0.25% emission reductions, rather due to statistical effects than to changes in traffic flow. Travel times were changed by a maximum of about 1%. However, the relaxation scenario consistently reduced travel times in all traffic situations, which suggests a further relaxation of the truck overtaking ban. We tested suspending the truck overtaking ban at high emission rates for the morning period from 5 - 11 a.m. The effects were particularly significant in the southbound direction, where the suspension led to a truck overtaking ban of only about 11% instead of the initial 70%. Travel times decreased by approximately 13%, and emission reduction reached about 4.3% for all emission components. These benefits in travel time were observed for both passenger cars and trucks, with more significant savings for trucks, see Figure 5. The emission reduction was primarily attributed to the trucks. Their behavior of acting as pace cars contributed to better traffic flow and reduced congestion. The impact was less pronounced in the northbound direction, as the truck overtaking ban was already lifted mostly. For a real-world implementation of such measures, certain factors must be considered. Trucks in PTV Vissim might behave differently from those in the real world, where they seldom overtake and typically stay in the right lane. Nevertheless, suspending the truck overtaking ban during peak times, possibly in combination with speed reductions, could potentially reduce congestion and emissions, making it a worthwhile measure to test in real-world settings.

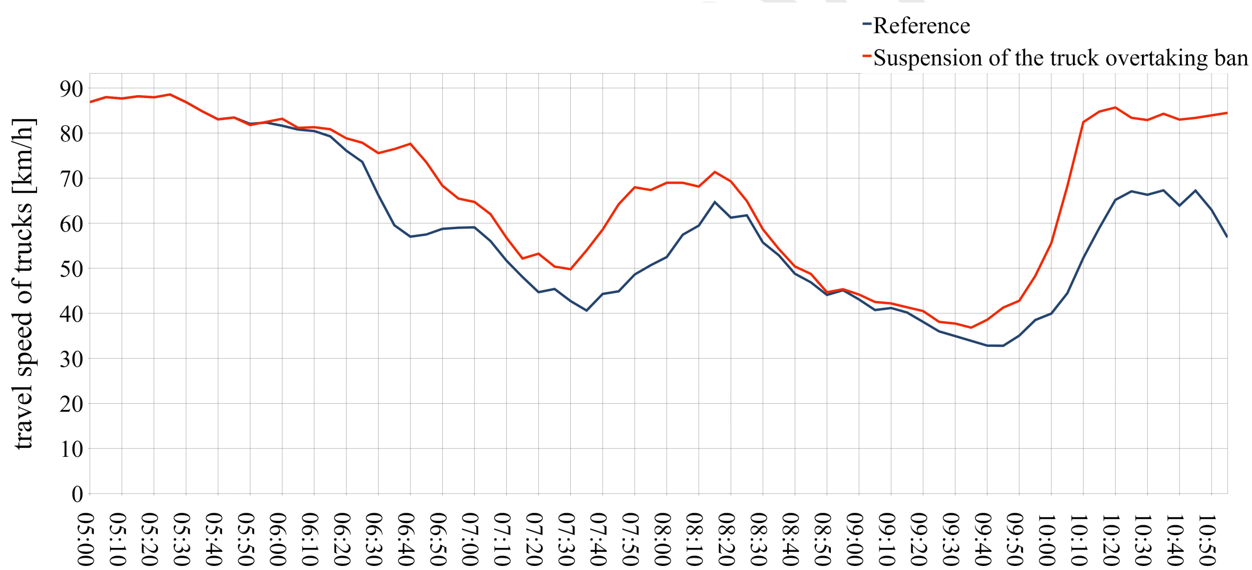

FIGURE 5 Travel speeds of trucks when suspending the truck overtaking ban (southbound direction, between AK 17 and AK 18)

Factors influencing the emission reduction potential

The impact of emission-reduction programs varies based on the starting situation. In this study, the absence of a general speed limit might decrease the estimated potential. At the same time, the already existing conventional FCS programs used as reference might indicate an additional impact of the emission programs on pollution.

Another crucial factor is the compliance among road users in following the displayed instructions. The compliance model used in this research is based on analyzing the conventional FCS compliance. Understanding how the level of compliance influences emission outcomes should be a focus of future research.

Further decisive factors are the choice of emission thresholds and the used emission model, which are discussed in the following.

A sensitivity analysis revealed that the selection of emission thresholds plays a crucial role in determining the effectiveness of the emission program. For the speed control program T100, the control pattern for different thresholds during the midday period is illustrated in Figure 6.

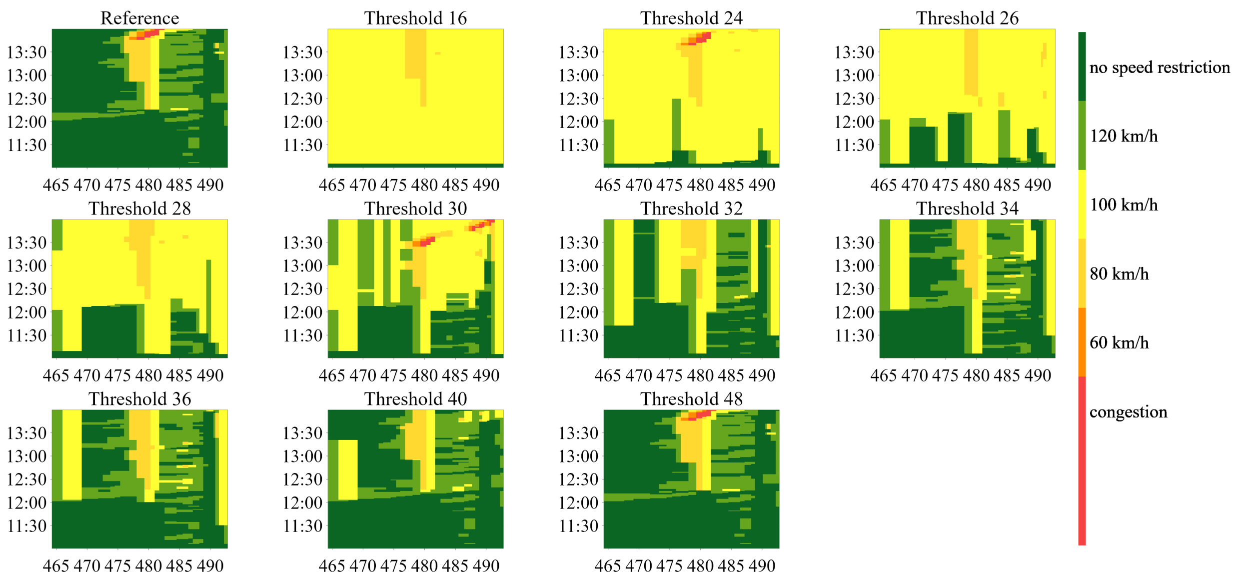

FIGURE 6 Control behavior of T100 for different emission threshold values (southbound direction)

The program was evaluated for NOx emission thresholds in steps of 8 g/min, refined further to steps of 2 g/min between 24 and 36 g/min. The deactivation threshold was consistently set 4 g/min below the activation threshold. We see a high sensitivity of the NOx threshold between 24 - 32 g/min (activation criterion). The analysis indicates significant variations in control behavior within this specific range. As a result, emission and travel time values also demonstrate higher sensitivity.

These findings emphasize the importance of carefully selecting threshold values based on the specific local traffic and environmental conditions, as well as the characteristics of the control program. It may be beneficial to calibrate the thresholds separately for each cross-section and potentially modify them over time, considering factors such as seasons or daytime variations.

In this research, the emission modeling was conducted using HBEFA. However, the basic HBEFA model used in this study, which relies on velocity thresholds to determine traffic states, might underestimate emissions.

We compared HBEFA to the microscopic emission model PHEMlight using a traffic flow toy model. To be comparable with PHEMlight, we adapted the original calculation procedure. Instead of considering traffic volume at a cross-section, we considered all vehicles driving from the cross-section until the next cross-section in a certain timestep. We incorporated vehicles' average speed and average driven distance within this section. Speeds were still used to determine traffic states, but the time fraction of immobile periods (TFIP) and the relative positive acceleration (RPA) were also explored.

As shown in Figure 7, the results for NOx showed slightly higher emissions than the original calculation when using the adapted method of spatial extension with speed and TFIP. The model PHEMlight also showed higher emission rates. The HBEFA model based on the RPA, led to a significant rise in calculated emissions. Although including microscopic driving dynamics is reasonable for an accurate emissions calculation, it must be emphasized that microscopic driving behavior is not faithfully represented in the simulation.

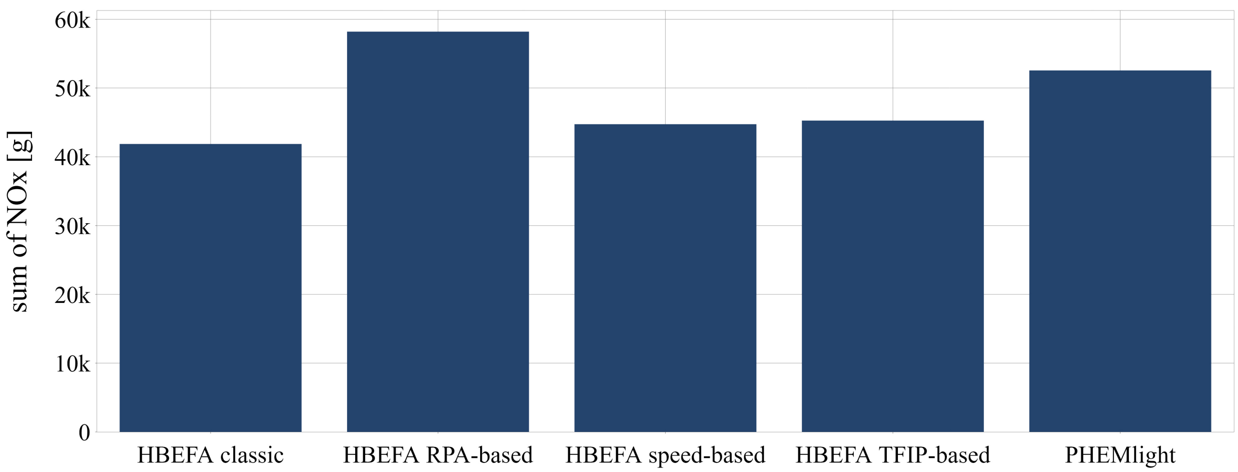

FIGURE 7 NOx emissions of a toy model using different emission model variations

In order to fully assess the environmental impact of emissions, there is a need to establish a more precise relation to measurable air pollution levels through emission dispersion models. This might be costly when used for traffic control. However, emission-based control approaches are still relevant for greenhouse gases as achieving overall global emissions reduction is relevant.

While the emission-based approach is straightforward to implement when an FCS is already available, it has limited overall effects. In order to comply with political climate protection objectives, measures like static speed limits and the transformation to ecological driving systems must be taken. Even though, in general, traffic flow optimization leads to an optimized emission scheme, this research did not consider traffic-shifting effects resulting from travel time reductions, which could affect emission outcomes.

CONCLUSION

This research explored emission-based algorithms of an FCS that have not been previously used or examined. These algorithms are mainly based on dynamic speed reduction which on the one side is a key factor for emission reduction and on the other provides enough flexibility to adapt to the traffic situation. Furthermore, the research highlights the direct impact of FCD on emissions by utilizing available resources without incurring high costs for immission measurement or modeling, making it practical for real-world application.

The conducted research revealed a potential of up to 10% in NOx reduction, up to around 9% for PM reduction and up to 6% in CO2 reduction for speed reduction programs, reducing the maximum speed limit to 80 km/h and 100 km/h whenever NOx emissions exceed a certain threshold. These values are reached in periods with medium traffic volumes.

The analysis further revealed that variations of elementary programs, such as platoon tracking, did not show the targeted efficiency improvement. It is more important to precisely calibrate emission thresholds and adapt them to local conditions as they showed a high sensitivity. An elevation of the truck overtaking ban during peak times showed positive effects on travel times due to congestion prevention leading to a reduction of emissions primarily on the side of trucks.

Further research in this area is warranted to understand the proposed measures' effectiveness comprehensively. For this purpose, it is essential to conduct practical field tests.

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