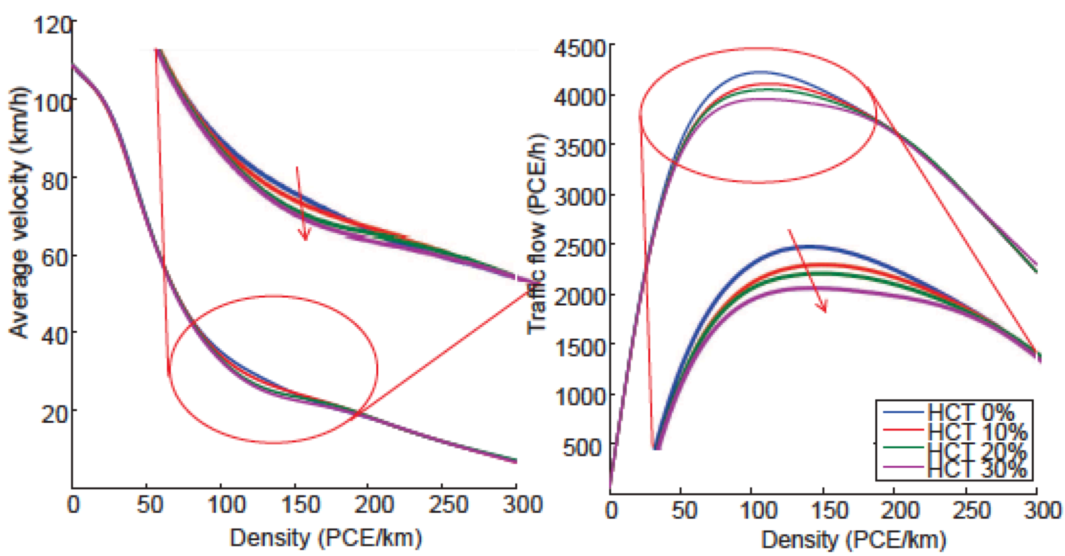
SAEFFLOW – Safety and efficiency analysis of HCT-Traffic flow indicators



Project within Integrerad Fordons och Infrastrukturutveckling inom FFI (FIFFI), 2014-03933

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Date 2017-01-30

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Content

1. Executive summary

In this research we aimed at elaborating algorithms and metrics to assess safety and efficiency impacts of High Capacity Transport (HCT, longer and heavier than the currently available trucks) via macroscopic key indicators, through traffic flow parameters. The applied methodology uses measurable flow related variables such mean speed, traffic flow and traffic density. The work places HCT related safety and performance analysis in a larger, network oriented context. The following major findings have been obtained by means of emulated results:

1) Among network, flow related parameters critical density increases with the penetration percentage of HCT, but throughput at peak hours slightly decreases. The effect of HCT is relevant around the critical density. Overall network fuel consumption and emission is reduced.

2) Two approaches are used for safety analysis. First, HCT crash risk is predicted on the basis of Swedish accident statistics by means of extrapolation in terms of vehicular length. Second, two real-time crash prediction models are being used in conjunction with traffic flow simulation. Changes in the crash precursors picture decrease in crash risk in HCT triggered flow.

2. Background

To achieve sustainability, the transport sector has to adapt to the continuously growing road transport demand and hence High Capacity Transport (HCT) becomes a feasible and attractive solution. HCT vehicles are larger and heavier than the currently utilized ones. Based on existing prediction, HCT penetration level will rise to 5% to 30% by 2030 [9], [3]. From adapting infrastructure to legislation issues, traffic network has to be prepared to accept HCT vehicles.

Recognizing the importance of HCT, research and development projects have been started in Sweden. In order to follow milestones defined in [9], a long truck combination are being tested in real traffic [10], existing data on regular truck crashes were extrapolated in [6] or Swedish performance based standards have been created in [11]. The latter project purports to approach regulation by standards for the Swedish HCT implementation. With increasing truck length, the weight of the transported goods will be increased too. Currently, Trafikverket is preparing supportive documents for the legislation issues of very heavy duty (74t) trucks. Individual safety/efficiency components of HCT are key ingredients to reach targeted goals [9], though the HCT impact on the entire traffic network is still unknown.

Longer and/or heavier vehicle combinations will change traffic variables and this proposal aims at understanding the effect of HCT in a larger, traffic flow context. Therefore, unlike previous studies, this project approached HCT traffic safety and efficiency from point of view of vehicles' interactions, thereof macroscopic flow. Instead of considering the behavior of a single HCT, we aimed at observing the changes caused by a certain amount of HCT vehicles. Our focus is to derive average valued quantities such as mean traffic speed, volume, or density [12] for HCT contained traffic flow. On the basis of these measurable variables, macroscopic safety (crash potential) and efficiency (e.g. fuel consumption, congestion parameters) can be assessed and hence benefits or drawbacks of HCT can be concluded. This concept enables sensitivity analysis of flow attributes in terms of extreme truck parameter setup (e.g. length. weight).

3. Objective

This proposal purports to address safety and efficiency analysis of High Capacity Transport (HCT) solutions. The aim is to elaborate algorithms and metrics to assess safety and efficiency impact of HCT via macroscopic key indicators, through traffic flow parameters. The applied methodology uses measurable traffic flow variables (macroscopic level). Algorithms have been found to define metrics for flow analysis when HCT included. Two main classes of metrics are considered; (1) safety, and (2) efficiency. The findings of this project are grouped in three parts.

Objective 1, Find and analyze useful HCT related macroscopic safety indicators, conclude their lower traffic level implications (i.e. implications for vehicle, microscopic level, identify safety critical traffic conditions for HCT). Find link to HCT legislation on the basis of macroscopic safety implications (averaged valued safety indicators, e.g. maximum allowable speed, HCT restricted/prohibited roads, traffic situation analysis and safety ranking).

Objective 2, Define the set of macroscopic efficiency indicators to quantify the benefits/drawbacks of HCT especially by means of introducing congestion parameters, eco parameters (energy/fuel consumption). Provide a comparative analysis of these parameters with and without (different levels of penetration) of HCT. Analyze changes in traffic network related capacity indicators (e.g. critical traffic volume, total time spent).

Objective 3, Define case study/studies by means of traffic model/simulator calibrated with HCT parameters obtained from truck industry/previous projects' outcome. Compute and analyze safety and efficiency HCT metrics. Increase HCT penetration level/alter HCT combination structure and predict HCT behavior. The analysis of the previously defined metrics allow us to observe patterns and trends for HCT included traffic (e.g. critical HCT penetration level, sensitivity analysis of HCT combinations in view of traffic safety and efficiency).

Investigating the changes caused by HCT in a large traffic flow context gave us a clear picture on how the average safety and efficiency of road traffic network is modified. For the derivation of these metrics, average valued variables are needed that are measurable by fixed/mobile detector stations. Hence, these metrics can be evaluated later whenever HCTs penetrate in real traffic. Finally, this project quantifies the effect (benefit/drawbacks) of HCT for a given road network taking vehicle interactions into account. This hence places HCT related safety and performance metrics in a larger context and concludes it in a road traffic environment. To reach the objectives of the project, a collaborative research platform among Swedish Road Administration, academia and truck industry is created. To find answer to the main research question behind the proposal, Trafikverket(TV) collaborateed with Chalmers University of Technology (Chalmers) supported from outside by Volvo Trucks Technology (Volvo GTT) and the HCT reference group.

4. Project realization

The research project has been carried out by Chalmers University of Technology, Gothenburg, Sweden. Data for calibrating the simulator has been provided by Trafikverket (topology, road segment selected) and the HCT reference group (HCT configuration applied, drivetrain profile, vehicle related data). Detailed technical results have been tabulated into [13], herewith a short project briefing is provided in terms of results.

The project defined objectives and connected to these milestones. These milestones have been progressively reached and completed, see next Chapter.

5. Results and deliverables

4.1. HCT inclusion in traffic network

To understand the effects of longer and heavier vehicles in traffic networks, first the current traffic composition is investigated. Based on recent year's statistical data from Swedish roads administration [1], [2], we create new vehicle classes (for HCT). We define their share based on their total kilometers traveled [13]. Next, an assumption is made to be able to compare different case studies: the volume of goods to be transported remains the same, but we replace traditional trucks with HCT. Based on the forecast in [3], by 2030 the share of HCTs for terminal transport falls between 15% and 30%. Although, in 2013, the share of HCT vehicles in real traffic is negligible, in this research, we assume that the HCTs in freight transport mount up maximum to 30% (we apply different penetration levels). We hence replace with HCT vehicles regular heavy ground vehicles (HGV). In terms of maximal transport capacity, one HCT vehicle (80t) equals approximately 1.5 long HGVs (60t) or 2 medium HGVs (40t). It means the total number of vehicles participating in traffic decreases. Traffic composition with HCT is shown in Table 1.

1. Table: Penetration of each vehicle class (%)

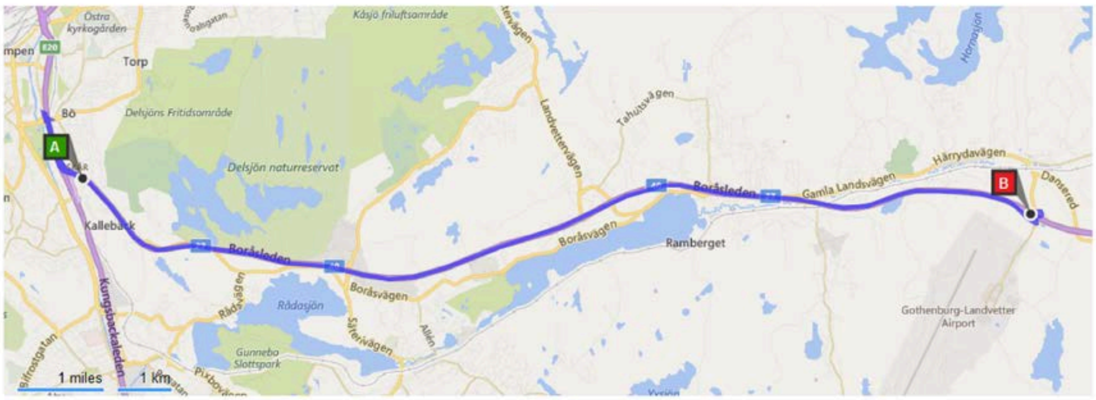
	Car	Short HGV (<15 m)	Medium HGV (15-18.65m)	Long HGV (18.75-25.25 m)	HCT (25.25-32 m)	Bus
HCT 0%	91.8	1.4	2.8	2.8	0	1.2
HCT 10%	92.2	1.4	2.25	2.25	0.7	1.2
HCT 20%	92.6	1.4	1.7	1.7	1.4	1.2
HCT 30%	93	1.4	1.13	1.13	2.13	1.21

In addition to the proposed vehicular split, different traffic scenarios with different restrictions for HCTs is investigated (lane and speed restrictions enforced in the simulation case study). Since HCTs will mainly travel on highways or national roads this setting is focused. Four restriction cases are investigated:

1. Unrestricted case: the permissible speed for passenger cars is 120km/h while for heavier vehicles it is 80km/h.
2. Speed restricted case: 90km/h speed limit is applied to passenger cars. There is no big difference between the speeds of cars, trucks and buses.
3. Lane restricted case: HCTs are restricted to the rightmost lane, so they cannot overtake. Speed limits are the same as in the unrestricted case.
4. Tempo 100: The general speed limit for every vehicle class is 100 km/h.

Since such long vehicles not yet travel on the Swedish road networks, vehicular simulation tool is used to analyze their effect. In the simulator the proposed vehicle classes are introduced with their own length, weight, power, desired speed distribution. These parameters are stochastically distributed and defined as distribution functions.

The simulation model makes it possible to generate and compare macroscopic traffic flow parameters for arbitrary traffic compositions and road conditions. A section of Swedish national road number 40 from Gothenburg towards Landvetter is modeled. The stretch is 12 km long, consisting of two and three lane sections and five on- and offramps (See Figure 1).

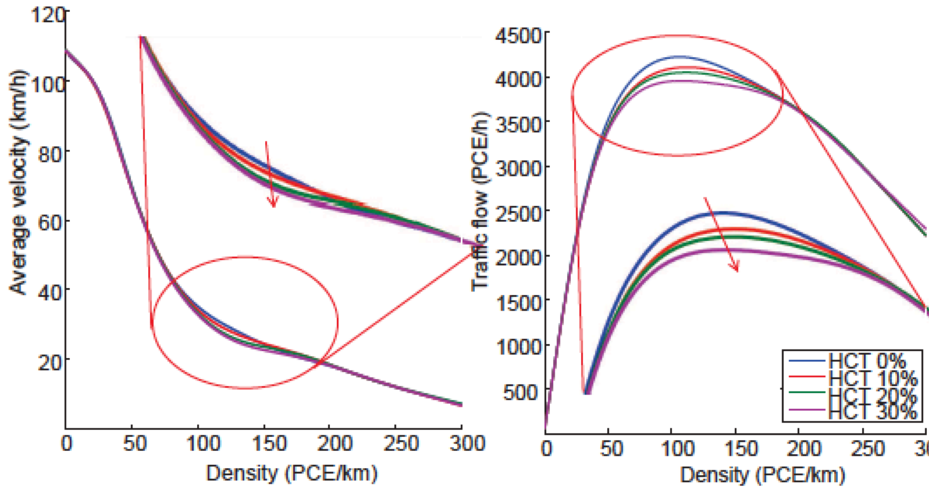


1. Figure: Modeled road section (source: Google maps)

Traffic volume calibration is based on loop detector data, using the database of Vägverket [4]. In the simulation scenarios a one day long measurement is used, altered with the proposed traffic compositions (Table 1).

HCT efficiency

Efficiency of HCT vehicles is analyzed via macroscopic indicators of traffic flow, such as average speed, road capacity, density, lane change rate. The basis for analysis is the fundamental diagram of traffic flow [12]. This diagram forms the relationship between road capacity and traffic density.



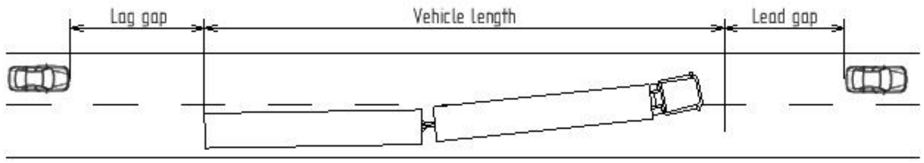
2. Figure: Fundamental diagram

Figure 2 depicts the average velocity and traffic flow as function of density HCT included. The latter is the so called fundamental diagram. Flow and velocity diagrams have an explicit (uniformity) relationship: $q = v(\rho) \cdot \rho$. q is the traffic flow, ρ the density and v the average velocity. The fundamental diagram is acquired by taking a 500 meters-long three lane highway section from the model and increasing the number of vehicles entering the network until it becomes fully congested. Flow and density values are homogenized using passenger car equivalents (PCE).

According to simulations HCTs only have significant impact around the critical density of a given road section. The peak capacity of the road segment decreases by approximately 2% per 10% HCT in the HGV fleet. Since HCTs can block traffic, the average velocity of the network decreases. The critical density increases when HCTs are introduced to traffic. This means congestion will form at higher densities, making the flow traffically speaking more stable.

The increment of critical density with longer vehicles is also shown analytically using a macroscopic traffic flow model.

The decrement in capacity is caused by lane changes: longer vehicles require more time to overtake or be overtaken and thus they may block traffic, reducing average velocity. Nonetheless, HCTs in traffic reduce total number of lane changes. In dense traffic longer vehicles cannot find large enough gaps to perform a lane change therefore these vehicles can be stuck behind slower vehicles, unable to accelerate to their desired velocity. This results in decrement in the macroscopic mean speed as it can be seen on Figure 2 around the critical density. It is harder to overtake longer vehicles and it is even harder to perform an overtaking (lane changing) maneuver with longer (and slower) vehicles (see Figure 3). It takes more time and can hold up vehicles at the downstream, further reducing the mean speed of the segment. This effect could become more significant than the decrement in lane changes. Vehicles not being able to travel with their desired speed results in increased travel delays. Delays become larger with larger HCT vehicle volume.



3. Figure: Lane changing HCT

Fuel consumption and emissions

In this efficiency analysis the total fuel consumption of the network and the emission of two pollutants (CO_2 and NO_x) are investigated. In order to compare total fuel consumed on the road network an adequate fuel consumption model is needed. The proposed model is based on the velocity profile and the efficiency of each vehicle's driveline [13]. From about the energy required to move a vehicle from its origin to its destination the required fuel mass is calculated. Fuel consumption of every vehicle is summed to obtain the total consumption of the network. Overall consumption of the network is compared at different HCT penetration levels. The total fuel consumption of the network decreases by approximately 1% per 10% HCT in the traffic flow. The reason for this decrement is that HCTs are more efficient in terms of fuel consumption, less HGVs are needed to transport the same amount of goods. On the other hand HCTs perturb traffic around them in such a way that the fuel consumption of other vehicles increase slightly. Fuel consumption related results are summarized in Table 2. CO_2 emission depends on the amount of fuel burned, therefore it follows similar trends as the fuel consumption.

NO_x emission depends on the air to fuel ratio and exhaust aftertreatment technology used. To this end a mean speed macroscopic emission model COPERT [5] is used to circumvent the modeling burden. In COPERT there is no data for HCT NO_x emissions. The expected HCT NO_x emission is extrapolated from the existing HGV groups in the model, based on their weight. By cumulating the mean speed of the traffic composition, total NOx emission is obtained. By reducing the number of HGVs on the road network by introducing more HCTs NO_x pollution can be reduced significantly. 10% HCT penetration reduces the overall NO_x emission by 1.5%.

2. Table: Fuel consumption

	HCT 0%	HCT 10%	HCT 20%	HCT 30%
Total fuel consumption	100%	98.77%	97.57%	97.07%
Car fuel consumption	100%	100.62%	100.82%	101.33%
HGV fuel consumption	100%	96.58%	92.94%	87.45%

HCT traffic safety

Impact of HCTs on traffic safety was investigated, using two different approaches. First, using Swedish traffic and crash data HCT crash risk is evaluated. Findings in [6] show decreasing crash risk with increasing vehicle size. Based on the kilometers traveled by each HGV category and the number of severe crashes occurred during the investigated time period cash rate is calculated. Since HCTs not yet travel on Swedish roads in large numbers there is no reliable information on their crash risk. To this end the crash rate of HCTs is extrapolated from the available data. Vehicles are grouped into categories based on their size and their accident rate is extrapolated to longer vehicles. The accident rate follows a decreasing trend as vehicle size increases. HCTs are as safe as or safer than existing long (25.25 m) combinations. For typical traffic compositions with HCTs included, macroscopic crash risk is evaluated. If the goods transport was done with more HCTs, instead of traditional HGVs during the examined period, the number of accidents resulting death or serious injury would be less. On the other hand accidents involving larger vehicles are more likely to be severe. There is not enough number of accidents with HCTs, to identify typical causes.

Two real-time crash prediction models are borrowed from the literature and used in conjunction with traffic flow simulation results to get a picture on how different HCT penetration levels alter crash risk. In these models crash precursors are defined, which are metrics to describe the relationship between accident frequency and macroscopic traffic flow indicators. They are based on traffic flow characteristics, road geometry and environmental variables. Evolution in a certain direction of these precursors can predict an accident on freeways. In this work two models are looked into in detail: [7] and [8].

It is not possible to use the aforementioned crash prediction models to tell the exact crash risk without calibration data. Individual precursors can be analyzed however. From the model it is known, how the change of a precursor changes crash risk. When HCTs are introduced to traffic, their presence alters traffic flow around them in terms of variance of speed, density, traffic volume etc., which are key variables in crash precursors. Environmental variables such as weather and road geometry are omitted from the precursors, because the focus is on longer and heavier vehicles and how their presence perturbs traffic flow. Road conditions shall remain constant.

In [7], crash frequency is defined as a function of a variety of traffic and environmental characteristics. In this model three traffic flow conditions affect crash risk: variation of speed over time (CVS), speed difference between upstream and downstream (S) and density (R). Oscillation in velocity be it in time or space assumes the flow is not stable and forecasts increased crash risk. Density is a meaningful precursor because it contains information about the number of vehicles on the network.

In [8], a crash prediction model is proposed and implemented in a variable speed limit control strategy. Two models are proposed: one for high speed and one for low speed regime. Based on the physical meaning of the terms in these models new precursors can be identified: occupancy, average volume (AQ) and the standard deviation of volume (DQ). The latter precursor is related to forming and dissipating congestion. There is a direct relationship between density and occupancy so if one decreases the other has to decrease too. Lane change rate (LC) can also serve as a precursor, since more lane change can lead to more lane change related conflicts.

With increasing HCT penetration levels variation of speed (CVS) shows a weak decreasing trend. By HCTs blocking traffic they also smoothen it, reducing fluctuations. Density (R) decreases because the total number of vehicles decrease on the road. Less dense traffic is safer. Average velocity (S) is approximately the same between upstream and downstream, no trend can be observed. Average volume (AQ) decreases, more HCTs mean less other HGVs. Standard deviation of volume (DQ) also decreases, HCTs make traffic flow smoother.

Four out of the six aforementioned precursors point toward decrement of crash risk while the other two do not clearly work against it. From the proposed precursors it can be assumed that crash risk decreases if longer and heavier vehicles are introduced into traffic. Results from crash precursors are in line with the results in the statistical approach.

Deliverables

The main deliverable is the project report [13] that has been composed by the following structure of milestones.

1. *Macroscopic traffic parameters for HCT on the basis of average valued traffic variables. (Objectives 1, Milestone 1).*

   The total number of vehicles on the road decreases by approximately 0.4% per 10% HCT penetration if the amount of transported goods remain unchanged. The total number of freight transport vehicles decrease by 5% per 10% HCT penetration.

   Increasing level of HCT in the traffic decreases the capacity of the road segment (approximately by 2% per 10% HCT).

   It is shown analytically using a macroscopic traffic flow model, that the critical density (where the road segment has its maximum capacity) is increasing, with longer vehicles on the road. This means, that the traffic flow remains stable at higher density levels, more vehicles are needed to congest a given road section. Presentation at HCT reference group has been given on this milestone.

2. *Elaboration of alternative methods and algorithms to calculate macroscopic safety indicators. Analysis of the generic properties of these metrics with special*

attention on legislation. Potential trends and patterns in safety metrics, (Objective 1, Milestone 2).

Change in crash precursors suggest decrement in crash risk in HCT flow. Longer vehicles tend to be safer, crash risk decreases with HCTs present.

First, HCT crash risk is predicted on the basis of Swedish accident statistics. Vehicles are grouped into categories based on their size and their accident rate is extrapolated to longer vehicles. For typical traffic compositions with HCTs included, macroscopic crash risk is evaluated. Second, two real-time crash prediction models are borrowed from literature and used in conjunction with traffic flow simulation results to get a picture on how different HCT penetration levels alter crash risk. In these models crash precursors are defined, which are used to create empirical relationship between accident frequency and macroscopic traffic flow indicators.

3. *Definition of HCT efficiency parameters in traffic flow context. Especially, HCT efficiency has been studied from point of view energy consumption, environmental load, congestion parameters cased by, (Objective 2, Milestone 3).*

Increasing number of HCTs causes the increment in fuel consumption for other classes but it is outweighed by the fuel saving because of there are less vehicles on the network (since less HCT vehicles are needed to transport the same amount of goods). There is approximately 1% fuel saving on the whole road network per 10% HCT penetration in the freight transport vehicle fleet. The fuel saving for HGVs is approximately 4% per 10% HCT. In the lane restricted case the overall fuel consumption is slightly higher than in the non-restricted case.
The CO2 emission follows similar trend as the fuel consumption. CO2 emission is also reduced.

NOx emission from road traffic comes mostly from heavy duty diesel engines. By reducing the number of HGVs on the road network by introducing more HCTs NOx pollution can be reduced significantly. 10% HCT penetration reduces the overall NOx emission by 1.5%.

Further fuel saving and reduced emission can be achieved in the short run by introducing HCTs to public roads, since these vehicles are more modern than the existing HGV fleet and falling into Euro V or Euro VI emission category.

Presentation at HCT reference group/VINNOVA/National Transport Conference has been given on this milestone.

4. *Numerical solutions to obtain network efficiency metrics, tools for their computation. Generic trends in HCT included traffic flow vs. the efficiency indicators. Conclude network level benefits of HCT, (Objective 2, Milestone 4).*

   Increasing HCT penetration causes significant change in the fundamental diagram around the critical density, and has negligible effect in the free flow and congested region which is more likely to occur in a real life scenario. The decrement in capacity is caused by lane changes: longer vehicles require more time to overtake or be overtaken thus blocking traffic, reducing average velocity. Nonetheless HCTs in traffic reduce total number of lane changes.

   Reduced average density also results in increased delay times. Delays increase as HCT penetration increase. except for the lane restricted case, but only for HCTs. It is because the flow in the HCT lane becomes more homogeneous.

5. *Comparative case study based evaluation of the results in simulation environment. Assessment criteria and evaluation of the proposed system for real-world technical information and infrastructure. (Objective 3 and Milestone 5).*

   The analysis is based on recent years statistical data from Swedish roads. A highway section near Gothenburg is modeled in simulation tool to serve as basis of the analysis. Simulation scenarios involve different HCT penetration levels, speed and lane restricted cases.

   Presentation at HCT reference group/VINNOVA has been given on this milestone

6. *Final report, documentation of results (All objectives, Milestones 6, deliverable).*

   A Vinnova final report and a technical report [13] has been created to cover the content.

5.1 Delivery to FFI-goals

Embedded into the FFI goals, this project answers the following transport efficiency and safety questions for long vehicle combinations (to be introduced on public roads):

What kind of effect does long vehicle combinations have onto traffic flow and hence traffic efficiency?

Milestone 1,3,6

How can we quantify HCT efficiency and safety in macroscopic flow context?

Milestone 1,3,6

What values do these indicators have in typical Swedish traffic conditions with different HCT penetration level?

Milestone 4,5,6

6. Dissemination and publications

6.1 Knowledge and results dissemination

OEM independent results for HCT efficiency and safety has been obtained that aims at supporting the Swedish Road Administration. Coupling of network related (traffic management) data has been elaborated into useful HCT metrics. These metrics can be used to apply to evaluate other HCT solutions (e.g. platooning). Connection of the project to vehicle centered safety (microscopic) may be connected to these results (with a mezoscopic traffic layer). The project comfirms the efficiency benefits of HCT included in flow context.

6.2 Publications

Regular presentations have been given to the High Capacity Transport Reference group in Gothenburg (3 times in 2 years, 2015-2016). On Vinnova project day, a presentation has been given in Stockholm (2016). Finally, part of the project results have been presented to the scientific transport community, at the National Transport Conference, Lund, 2016. Technical details are in [13]. A journal paper is in the pipeline to document results.

7. Conclusions and future research

The impact of longer and heavier vehicles was investigated in a macroscopic traffic flow context. The analysis is based on recent years statistical data from Swedish roads. A highway section near Gothenburg is modeled in simulation to serve as basis of the analysis. Simulation scenarios involve different HCT penetration levels, speed and lane restricted cases. Besides the benefits of HCTs, they have some negative effects on traffic flow too.

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