The negative effects of homogeneous traffic on merging sections

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Abstract: Homogeneous traffic flows are believed to be better in absorbing disturbances, raise capacity and stimulate traffic safety. Measures to make traffic more homogeneous are therefore often taken to increase capacity. This paper shows that the ability of a traffic flow to deal with traffic coming from an on-ramp reduces when the through flow becomes more homogeneous. A motorway was modelled in the micro-simulation model AIMSUN2 and traffic of different levels of homogeneity was confronted with on-ramp traffic. The research confirms the hypothesis that the less homogeneous traffic is, the more acceptable gaps for merging vehicles become available. So homogeneity measures should always be combined with on-ramp metering which both recognises and acts upon the new distribution of critical gaps in the flow.

Key Words: Homogeneous traffic; gap acceptation; merge; on-ramp metering; bottleneck; capacity.

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1   Introduction to homogeneous traffic

One of the leading works in the field of traffic, the Highway Capacity Manual (HCM) [5], does not give a definition on homogeneous traffic, although the term is used more and more often in relation to traffic congestion related problems. Although the HCM does not deal with homogeneous traffic the issue of homogeneity of traffic has been applied to different characteristics of the flow as the distributions of speed, density and flow, lane changes, time-to-collisions on all levels of aggregation. Speed, flow and density and their relations have been recognised by Greenshields [2] and studied extensively ever since. How differences and fluctuations of these characteristics influence traffic have been studied ever since Lighthill and Witham [7]. Studies into traffic topics that deal with distribution indirect deal with homogeneity issues.

When homogeneity measures are taken, for instance by introducing a dynamic (and lower) speed limit on a road, not only speeds are levelled more, but also the number of lane changes is reduced, the average time-to-collision changes and more characteristics of the flow change. The most common goal of homogeneity measures, capacity increase, however is not always reached [3].

This paper deals with five aspects of homogeneity of a traffic flow and to what extent these aspects influence bottleneck capacity. The bottleneck researched (with a microscopic traffic flow model) is an on-ramp with a very high flow-rate (usually the reason for the capacity problems). The five aspects are:

1. Speed differences within lanes; the speed differences of successive vehicles are reduced to create a more homogeneous flow.
2. Speed differences between lanes; the speed differences between vehicles in different lanes are reduced.
3. Number of lane changes; the number of lane changes is reduced.
4. Number of clusters of vehicles; the number of clusters of vehicles is reduced.
5. Time-to-collision per vehicle; the number of very small time-to-collisions is reduced.

For every aspect the capacity of the original flow (non-homogeneous) is compared to the capacity of a homogeneous flow and a semi-homogeneous flow that lies in between.

2 Simulation set-up

An on-ramp bottleneck was modelled in Aimsun2.

2.1 Aimsun2

Aimsun2 (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) is a microscopic traffic simulation program that can deal with different traffic networks: urban networks, freeways, highways, ring roads, arterial and any combination thereof. It is mainly useful for testing new traffic control systems and management policies without having to implement in a real traffic network. Aimsun2 follows a microscopic simulation approach, which means that the behaviour of each vehicle in the network is continuously modelled throughout the simulation time period, according to several behavioural models (e.g., car following and lane changing). The system provides highly detailed modelling of the traffic network and it distinguishes between different types of vehicles and drivers [1].

Aimsun2 has a number of parameters that can be used to make different aspects of the traffic flow more or less homogeneous. This study does not aim to show the effects on an existing on-ramp (which would have needed extra calibration), but shows the capacity differences between homogeneous and less homogeneous traffic at a saturated on-ramp.

2.2 Network
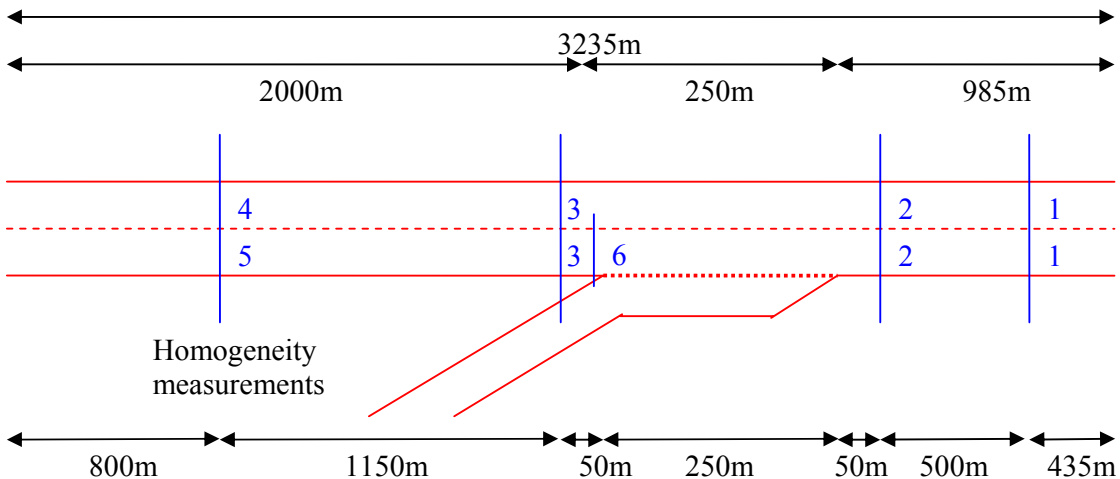
Figure 1: Simulation network of the on-ramp, including detector numbers.

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A two-lane motorway and an on-ramp were modelled. The length of the motorway section is 3235 meters: 2000 upstream of the on-ramp, 250 meters of on-ramp itself and 985 meters downstream of the on-ramp. The long lengths upstream of the merging-section are used to let the traffic that is put on the network through a normal distribution evolve into realistic rates of arrival during a peak hour .

Detector 1 measures potential spill-back that might interfere with the capacity measurement of this bottleneck.
Detector 2 measures the flow that runs through the bottleneck (and capacity, see section 3).
Detector 3 measures speed and is used to indicate wetter the bottleneck is suffering congestion.
Detectors 4 and 5 check homogeneity of the through traffic.
Detector 6 monitors gap distribution of the through flow near the on-ramp.

2.3 Simulation of characteristics of homogeneous traffic

This study quantifies the effect on capacity of several aspects of homogeneity. It does not intent to give ways of how to create these levels (if wanted). The five aspects of homogeneous traffic are modelled one by one. All simulations take 1 hour of real-time simulation and all simulations are repeated 10 times, using different 'random seeds'. This way all measurements become stochastic and more reliable conclusions can be drawn at the end. The 1 hour simulation time is divided into 12 periods of 5 minutes, with increasing flow. This is done to be able to estimate the capacity of the bottleneck using the product-limit method (section 3).
The product-limit estimation method needs the bottleneck to become homogeneous congested (in the sense of Helbing and Treiber [4]), without any disturbances running upstream as shockwaves or oscillating congested traffic. To reach that a large traffic flow was put on the on-ramp as can be seen in Table 1.

Table 1: Origin and composition of traffic.

Origin	Passenger cars (1PCE)	Short Trucks (1.5 PCE)	Long Trucks (2 PCE)	Total number of vehicles / Total of PCE
Motorway	2486	311	311	3108 / 3575
Onramp	684	86	86	856 / 985
Total	**3170**	**397**	**397**	**3964** / 4560

3   Capacity measurement using product-limit method

The product-limit estimation method that is used to estimate capacity is an easy statistical estimation tool introduced by Kaplan-Meyer to estimate the distribution of life span. For handling of this method see for instance Lawless [6].

We define I(t) as the flow at time t (in minutes) at detector 2.

One out of the two combinations below will always be observed:

- {I(t) in combination with no congestion at the bottleneck}; is interpret as Capacity (t) > I (t)

- {I(t) in combination with congestion upstream of the bottleneck (detector 3) and no congestion downstream of bottleneck (detector 1)}; is interpret as Capacity (t) = I (t).

The product-limit estimation of the capacity F_c is calculated by sorting the flow from low to high and taking the product:

$$F_c(x) = \prod_{j:I_j \leq x} \frac{n_j - 1}{n_j}$$ (1)

in which n_j = number of occasions with $I_k > I_j$, and variance

$$Var\{F_c(x)\} \cong F_c^{\,2}(x) \cdot \sum_{j:I_j \leq x} \frac{1}{n_j \cdot (n_j - 1)}$$ (2)

Only if data complies to:

V_c (t) > 70 km/h at detector 1 and
V (t) < 70 km/h at detector 3

the flow data from detector 2 is used for capacity calculations.

4   Results

4.1   Speed differences in one lane

General belief is that large speed differences between vehicles in the same lane have a negative effect on capacity. To test this hypothesis two parameters in Aimsun2 were changed; 'maximum desired speed' and 'speed acceptance'. The second parameter indicates to what level drivers are willing to accept the speed of the vehicle in front of them although it might be lower than their own desired speed. Changes in these parameters created a flow that had less speed differences between successive vehicles in a single lane.

The influence of the measures on the traffic flow is shown in figures 2a and 2b. The speed differences of the non-homogeneous and the homogeneous case are presented, together with the standard deviation. The semi-homogeneous traffic is left out, but lies between the non-homogeneous and the homogeneous case.
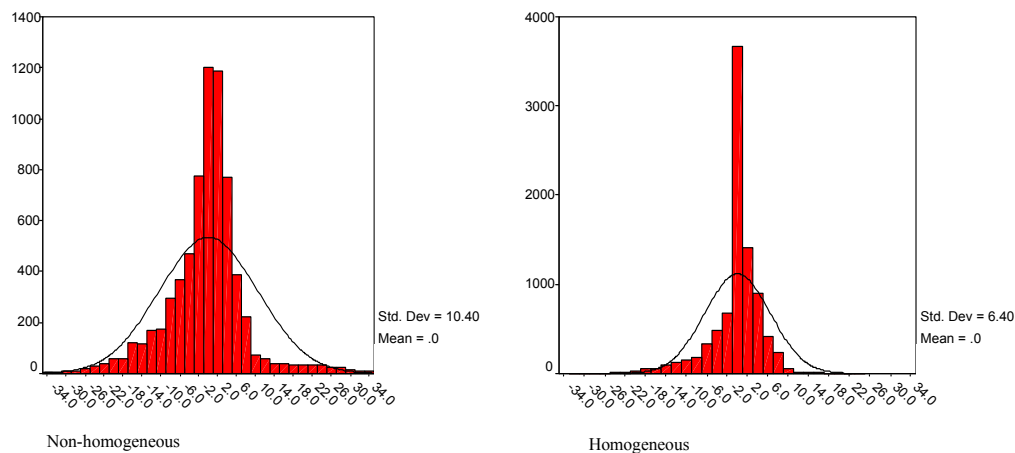
Figure 2a /b: Number of speed differences between successive vehicles.

It can be seen that the speed differences of vehicles in the traffic flow reduce through the changes in parameters. The results of the parameter changes are measured 1150 meters upstream of the bottleneck, on the detectors 4 and 5. Detector 2 is used for capacity estimates, using the Kaplan-Meyer estimation.
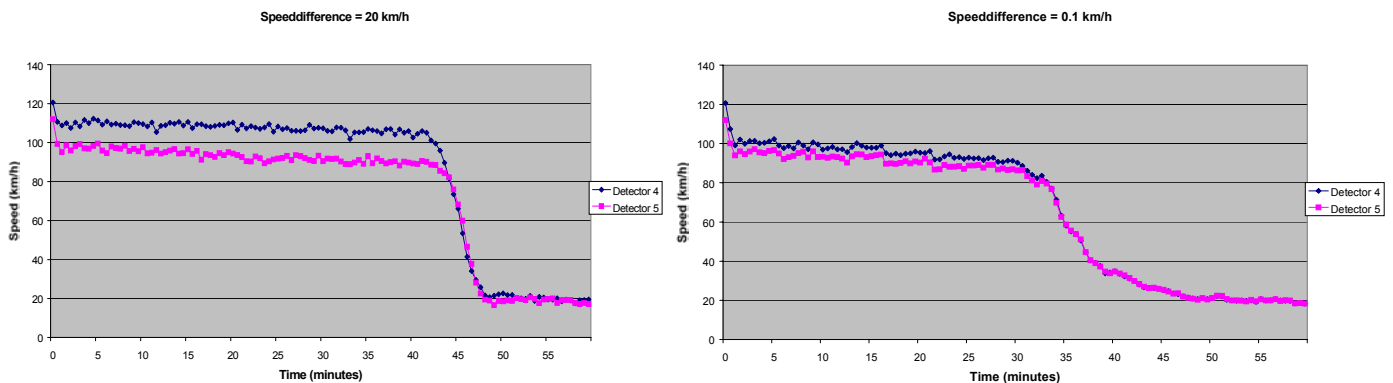
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Table 2: Capacity measurements of flows.

Homogeneity characteristic	Capacity in PCE (95% confidence interval)			
	Non-homogeneous (Original)	Semi-homogeneous	Homogeneous	Performance
Speed differences within lanes	4106 (4035-4142)	4092 (4043–4119)	3968 (3940-4030)	**- 3.4%**

The homogeneous traffic flow, with a reduction of speed differences between successive vehicles, shows a significant decrease in capacity of minus 3.4% compared to the original (non-homogeneous) flow.

4.2   Speed differences between lanes

General belief is that large speed differences between lanes have a negative effect on capacity. The speed differences between vehicles in different lanes were reduced by changing the parameter 'maximum speed difference' to test this. The acceptable speed difference between lanes was altered form 20 (non-homogeneous) to 10 (semi-homogeneous) and to 0.1 (homogeneous) km/h.

Figure 3a and 3b show the effects of the change in parameters on the traffic flow, measured upstream of the bottleneck on detectors 4 and 5.

Figure 3a/b: Speed difference between lanes.

Besides speed differences between lanes reducing, the onset of congestion happens 10 minutes earlier in the homogeneous case (speed difference = 0.1 km/h). The time of the onset does not influence the capacity measurements; capacity depends on throughput levels.

Table 3: Capacity measurements of flows.

	Capacity in PCE (95% confidence interval)			
Homogeneity Characteristic	Non-homogeneous (Original)	Semi-homogeneous	Homogeneous	Performance
Speed differences between lanes	4106 (4035-4142)	3964 (3926-4023)	3881 (3824-3950)	**- 5.5%**

The homogeneous traffic flow shows a significant decrease in capacity of minus 5.5% compared to the original (non-homogeneous) flow.

4.3 Number of lane changes

General belief is that more lane changes have a negative effect on capacity. To test this the number of lane changes is reduced by 100% (keep your lane) using a 'solid line' between the lanes on the highway from the feeding point down to the bottleneck. Because an option in which half of the lane changes of the original traffic flow take place can not be created by a 'solid line', the parameters 'percent overtake' and 'percent recover' are adapted to create the semi-homogeneous case.

Table 4: Capacity measurements of flows.

	Capacity in PCE (95% confidence interval)			
Homogeneity characteristic	Non-homogeneous (Original)	Semi-homogeneous	Homogeneous	Performance
Number of lane changes	4106 (4035-4142)	4071 (4009-4106)	3988 (3940-4009)	**- 2.9%**

The homogeneous traffic flow shows a significant decrease in capacity of minus 2.9% compared to the original (non-homogeneous) flow.

4.4 Number of clusters of vehicles

The definition for a cluster we used is: a group of five or more vehicles on the same lane of the motorway, each with a time gap of less than 1.5 seconds. This definition leaves out the first vehicle of the cluster and includes the 'followers' in the group.
To create different levels of clustering the parameter 'speed acceptance' is changed. The number of clusters detected at detectors 4 and 5 is shown in table 6.

Table 5: Number of clusters.

	Non-homogeneous (Original)	**Semi-homogeneous**	**Homogeneous**
Detector 4	36	27	21
Detector 5	2	2	3

Table 6: Capacity measurements of flows.

	Capacity in PCE (95% confidence interval)			
Homogeneity characteristic	Non-homogeneous (Original)	Semi-homogeneous	Homogeneous	Performance
Number of clusters of vehicles	4106 (4035-4142)	4072 (4037-4112)	3985 (3954-4016)	**- 2.9%**

The homogeneous traffic flow shows a significant decrease in capacity of minus 2.9%, compared to the original (non-homogeneous) flow.

4.5   Time-to-collision per vehicle

More homogeneous traffic has less very small time-to-collisions, which are an indication for speed-changes and speed disturbances. To simulate traffic with fewer small time-to-collisions the parameter 'maximum desired speed' was set lower. Figures 4a and 4b illustrate that a traffic flow with much less small headway was realised. Time-to-collisions measurements took place at detectors 4 and 5. Just the time-to-collisions from minus 15 to 15 seconds are shown.

Non-homogeneous   Homogeneous
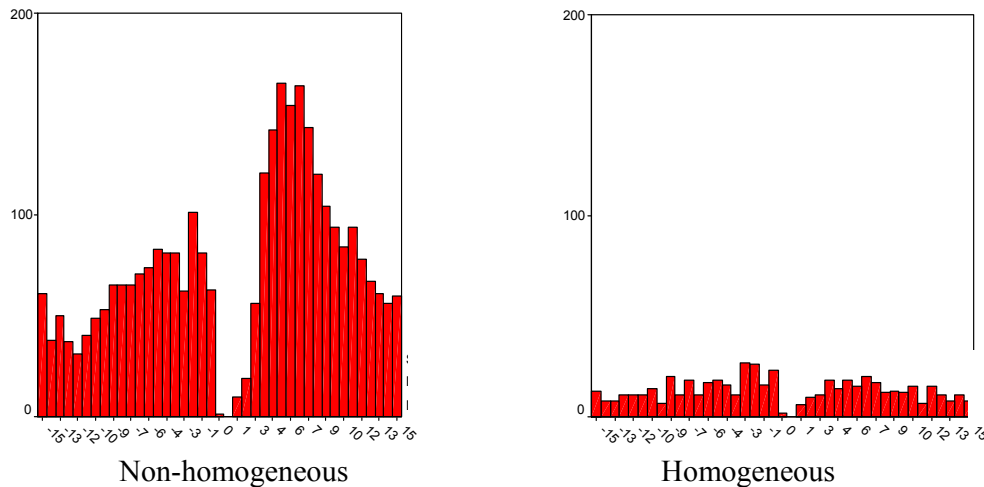
Figure 4a/b: Time-To-Collisions in different flows.

The amount of small time-to-collisions reduces dramatically.

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Table 6: Capacity measurements of flows.

	Capacity in PCE (95% confidence interval)			
Homogeneity characteristic	Non-homogeneous (Original)	Semi-homogeneous	Homogeneous	Performance
Time-to-collision per vehicle	4106 (4035-4142)	4078 (4014-4100)	4016 (3961-4043)	**- 2.2%**

The homogeneous traffic flow shows a decrease in capacity of minus 2.2%, compared to the original (non-homogeneous) flow.

5   Explanation of the Results

Table 7 shows the effects of the parameter and network changes, which cause one or more effects of homogeneity. It is clear that all flows with elements of homogeneity show reduced capacity compared to the original flow.

Table 7: Overview of capacity measurements.

	Capacity in PCE (95% confidence interval)			
Homogeneity Characteristic	Non-homogeneous (Original)	Semi-homogeneous	Homogeneous	Performance
Speed differences within lanes	4106 (4035-4142)	4092 (4043–4119)	3968 (3940-4030)	**- 3.4%**
Speed differences between lanes	4106 (4035-4142)	3964 (3926-4023)	3881 (3824-3950)	**- 5.5%**
Number of lane changes	4106 (4035-4142)	4071 (4009-4106)	3988 (3940-4009)	**- 2.9%**
Number of clusters of vehicles	4106 (4035-4142)	4072 (4037-4112)	3985 (3954-4016)	**- 2.9%**
Time-to-collision per vehicle	4106 (4035-4142)	4078 (4014-4100)	4016 (3961-4043)	**- 2.2%**

Next to these results visual inspection of the simulations showed that merging from the on-ramp onto the motorway is a recurrent problem, especially in homogeneous flows. This gave raise to the hypothesis that homogeneity of the traffic flow reduced the number of acceptable gaps, available for merging traffic. The gap distribution was measured on detector 6 and is shown in figures 5a and 5b.

Non-homogeneous   Homogeneous
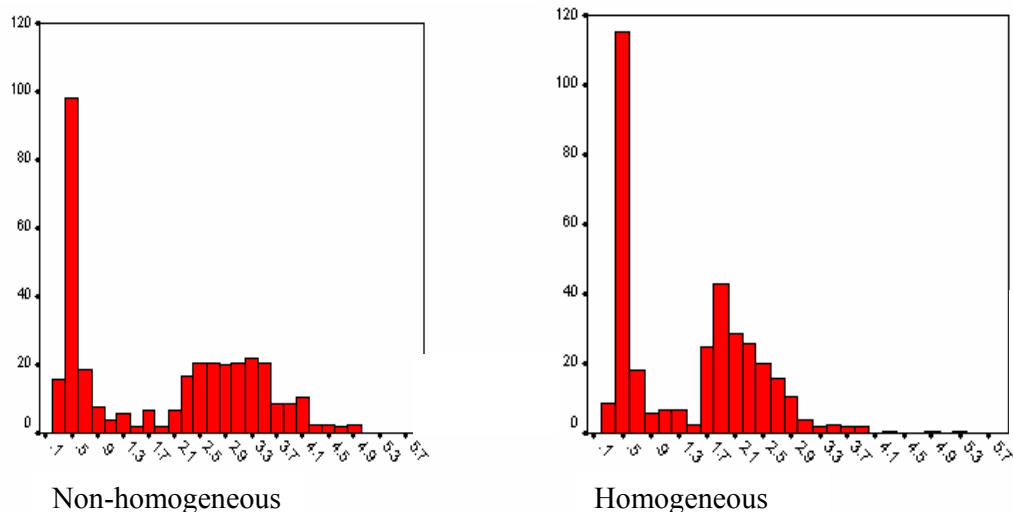
Figure 5a/b: Example of gap distributions.

Both figures show two peaks. The first peak corresponds to jammed traffic with very short headway. Once traffic is congested the homogeneous and non-homogeneous case are almost identical, but the average headway of the second peak is significantly larger when the traffic is not homogenised. Saito [8] shows that the headway acceptable for on-ramp traffic to merge is as large as 3 seconds. In the homogeneous case only 5% of the headways comply with this, while in the non-homogeneous case 30% of the headways on the right lane is over 3 seconds.

6   Conclusions

Aspects of homogeneity which are presumed to have a positive effect on capacity reduce capacity at on-ramp bottlenecks. Systematic "redistribution" of gaps the main flow reduces the number of opportunities for on-ramp vehicles to merge into the main flow and causes a traffic jam on the on-ramp and eventually the motorway itself.

7   Recommendations

Homogeneity measures and on-ramp metering are used to keep traffic flowing in bottlenecks. Traditionally these measures do not communicate. This paper shows that the effect of homogeneity on bottleneck capacity is negative if the traffic on this on-ramp is not guided, for instance by on-ramp metering. To be able to take homogeneity measures, which are positive for both capacity and safety outside bottlenecks and need a significant period of time and length of lane to sort its effect one should install on-ramp metering that incorporates the new homogeneous traffic situation. No homogeneity measures without on-ramp metering that recognises the new gap distribution and behaves accordingly should be taken.

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