Exam CIE-4821-09
Traffic Flow Theory and Simulation

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The exam has 6 questions. 43 points can be obtained, which are specified per question and subquestion. Some questions might require more time than others, so *use your time wisely*! The total time available for this exam is 3 hours.

Remarks:

- Allowed: calculator (but no smartphones...), self-made equation sheet (1 double sided A4 max)
- Put labels at all your graph axes.
- If a *sketch* is asked, there is no need for an exact drawing. Do make sure, though, that it is clear whether points lie higher or lower or on one line, and that this is correct.
- Your answer will be judged on the good elements in there, but for all wrong answers points will be deducted.
- For some questions, an indicative number of words is given as guidance for the required level of detail. Your answer may be shorter or longer.
- Make sure you provide the calculus procedure as well as the result in order to get the maximum points.

Question	Points
1	5
2	8
3	3
4	9
5	13
6	5
Total:	43

1. Short questions

Total for Question 1: 5

(a) **What does a Macroscopic Fundamental Diagram describe? Make sure your answer shows clearly the differences between an MFD and a fundamental diagram.** (2)

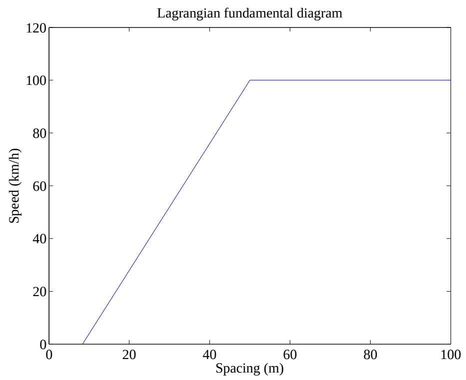
Solution: It averages the flow and densities (0.5) *for an area* (by which it differs from the regular FD) (1) and relates them to each other (0.5)

(b) **What is qualitatively the effect of inhomogeneity in the network on the MFD? (No explanation needed)** (1)

Solution: The average flow decreases for the same average density if the traffic is distributed less homogeneously over the network.

(c) **In Lagrangian coordinates, the fundamental diagram is often expressed in spacing (horizontal) - speed (vertical) form. Sketch a fundamental diagram in the spacing-speed plane** (2)

Solution: The speed is increasing with increasing spacing (0.5). There is a minimum spacing (0.5) and a maximum speed (0.5). Plot: 0.5



2. From car-following to a fundamental diagram

Total for Question 2: 8

The optimal velocity model is a car-following model specifying the acceleration a as follows:

$$a = a_0(v^* - v) \tag{1}$$

In this equation, v is the speed of the vehicle, and a_0 a reference acceleration (tunable parameter, constant for a specific vehicle-driver combination). v^* is determined as follows:

$$v* = 16.8(\tanh(0.086(\Delta x - 25) + 0.913)) \tag{2}$$

In this equation, Δx is the distance (in meters) between the vehicle and its leader.

(a) **Explain qualitatively the working of this car-following model; i.e. comment on these two equations.** (2)

> **Solution:** Vehicles have a desired speed v^* which is determined by the distance to their leader (1). The acceleration is proportional to the difference between their speed and the desired speed.

(b) **What are the conditions for which a fundamental diagram holds?** (1)

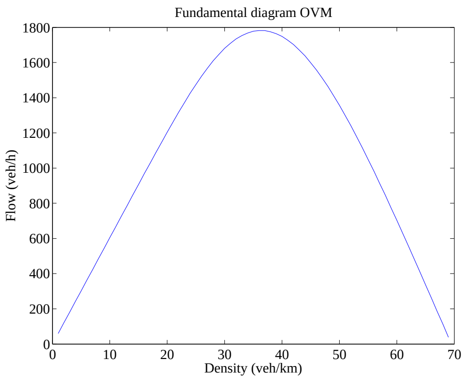
> **Solution:** Traffic must be stationary and homogeneous

(c) **Derive the expression a fundamental diagram (flow as function of density) for these conditions using the OVM model** (4)

> **Solution:** If traffic is stationary, the acceleration is 0 (1), so $v = v^*$ (1). Realising that $k = 1/\Delta x$ (0.5), or correcting for the units (density is in veh/km!) we find $k = 1000/\Delta x$ (0.5), leading to:
>
> $$v = 16.8(tanh(0.086((1/k) - 25) + 0.913)) \quad (3)$$
>
> (0.5) This is the speed in m/s, which should be translated into km/h, so:
>
> $$v = 3.616.8(tanh(0.086((1/k) - 25) + 0.913)) \quad (4)$$
>
> (0.5) Now applying q=ku=kv (0.5), we find
>
> $$q = k3.616.8(tanh(0.086((1/k) - 25) + 0.913)) \quad (5)$$
>
> (0.5)

(d) **What are the values capacity, free speed and jam density (either derive the value or use you graphical calculator to determine this – you may round numbers to the precision of your liking...)** (1)

> **Solution:** The fundamental diagram is shown below:



From this, we read a capacity of approximately 1750 veh/h, the free flow speed is approximately 60 km/h and a critical density of approximately 70 veh/km(1).

3. MOBIL lane change model

Total for Question 3: 3

Consider the mobil lane change model. A driver c has several options: change lanes to the left, to the right or stay in his current lane. For each of the options a total utility (denoted U_{tot}) can be calculated.

$$U_{\text{tot}} = U_c + p \sum_{i \in \text{other drivers}} U_i \tag{6}$$

The utility for the driver i U_i is assumed to be its instantaneous acceleration, as computed using a car-following model (the Intelligent Driver Model – although the specific model is not relevant for the question). The driver is assumed to take the option with the highest utility.

(a) **Explain the working of the model in words** (2)

Solution: Drivers are expected to change lanes whenever it is beneficial for them (measured in terms of acceleration) (1). They do take the other drivers' benefit into account, but less then their own (at factor p) (1).

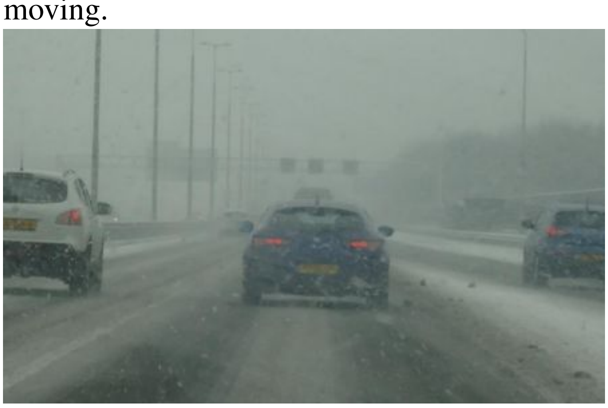
(b) **What value for p can be expected** (1)

Solution: It can be expected that drivers take other drivers into account (p>0), but value their benefits less then their own (p<1).

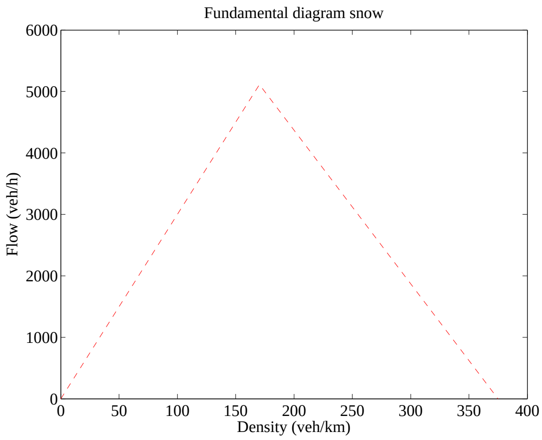
4. Snow plow

Total for Question 4: 9

During a winter night, a 30 cm snow covered a three lane motorway fell. Traffic is still moving.



This changes the traffic operations. Assume a triangular fundamental diagram. The free flow speed reduces to 30 km/h, the jam density to 125 veh/km/lane. The capacity is 5000 veh/h.



A truck spins and cannot move further, thereby blocking the road completely, not allowing other vehicles to pass. This leads to a traffic jam. The inflow is 1000 veh/h.

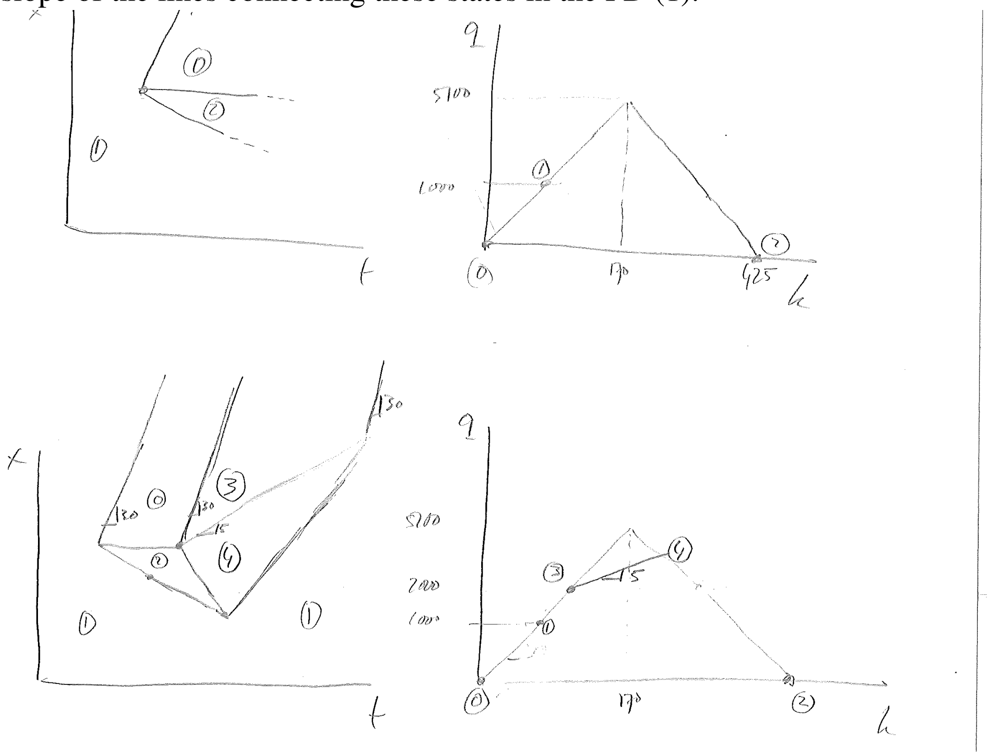
(a) **Draw the resulting traffic operations in a space time plot and in the fundamental diagram. Calculate all shock wave speeds.** (4)

Solution: Once the trucks come to a complete stop, upstream an congested area at jams density will be created (0.5); downstream, there will be an empty road (0.5). There are three shock waves. One with the free speed (30 km/h) separating the empty road with from the initial state (1). One at the location of the stopped trucks, separating the empty road from the jam state, at 0 km/h (1). Finally, there is a wave at the tail of the queue, propagating at a speed of $\Delta q/\Delta k$=1000/((1000/30)-425)=-2,5 km/h (upstream). (1)

A snow plow comes to free the vehicles that are stuck. After freeing the vehicles, the snow plows clear two of the three lanes of the motorway. Thereby, they drive at 5 km/h on the motorway. The capacity of vehicles passing the snow plough on the left lane is 2000 veh/h. The inflow on the road is 1000 veh/h.

(b) **Sketch the traffic operations in a space-time plot and in the fundamental diagram. Explain how you construct the graphs. (No point given here for the beginning, discussed in question b)** (5)

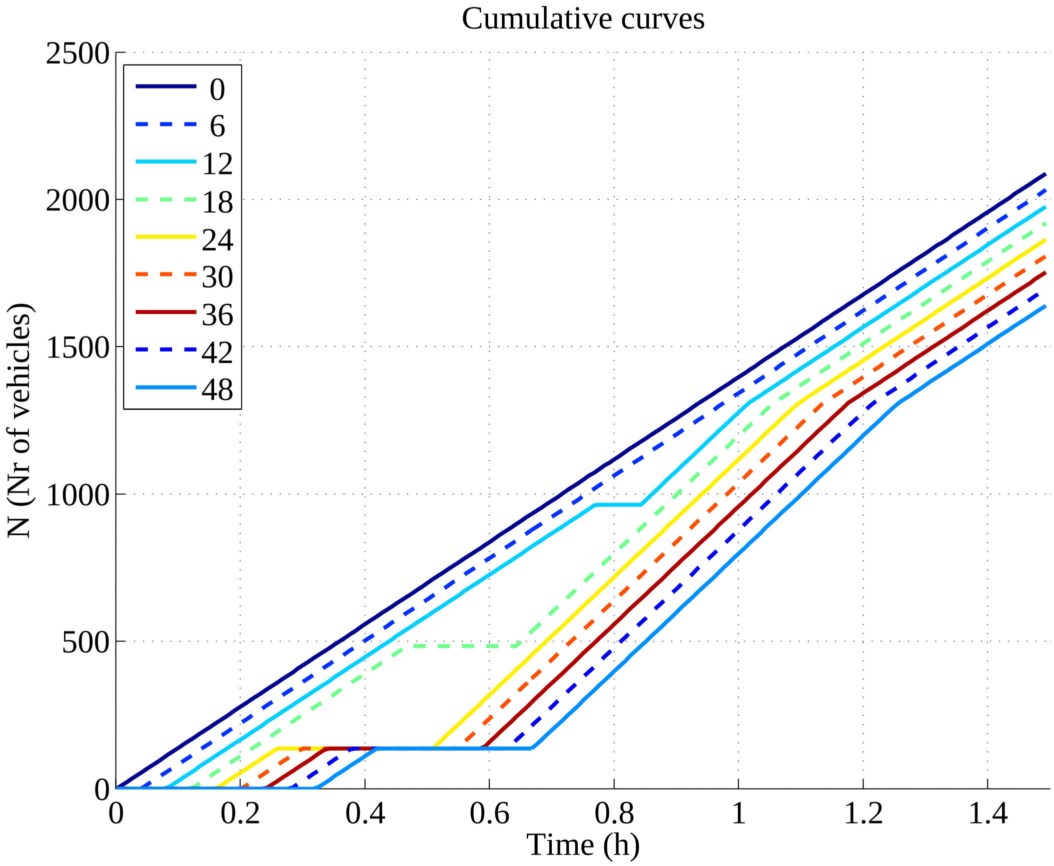
Solution: The start is the same as described in b. Then, at the head of the queue, vehicles are freed. The fastest vehicles, passing the moving bottleneck, will drive at a free flow speed of 30 km/h (1, including drawing in xt). The snow plows will form a moving bottleneck driving at 5 km/h (1, including drawing in xt). Downstream of this moving bottleneck there will be a free flow (0.5) traffic state with a flow of 2000 veh/h (given, 0.5) – this is state 3. The plows will form a moving bottleneck, and hence the separation of two traffic states, a congested upstream (state 4, unknown yet) and an uncongested downstream (state 3). (0.5 point). Plotting: 0.5 point. State 4 can be found by plotting the shock wave in the fundamental diagram, from state 3 upwards with a slope of 5 km/h (1). The shock wave speeds between 4 and 1, as well as between 3 and 1 can be found by the slope of the lines connecting these states in the FD (1).



5. Cumulative curves

Total for Question 5: 13

The graphs show cumulative curves for different locations along the road. The legends shows the distances in km from the beginning (i.e., upstream end) of a road. For the remainder of the question, reasoning is more important than exact readouts from the graph. When using graph readouts, please state so explicitly and *note the values you read from the graph*.



(a) **Explain the traffic state, mention a possible cause (e.g., "different speed limits for different sections", "peak hour jam") and explain why** (3)

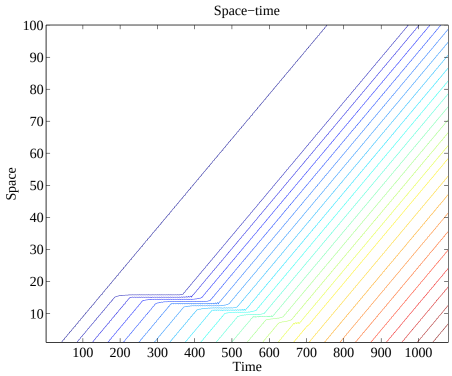
> **Solution:** The inflow is constant (constant raise of N at x=4 - 1 point), but the outflow is temporarily zero (no extra vehicles temporarily in the graph (1). Hence, there is a temporal blocking (0.5) completely blocking the flow. (0.5)

(b) **Estimate is the total delay encountered here** (3)

> **Solution:** The total delay can be derived from the area between the cumulative curves (1). In this case, we compare the cumulative curves where there is no delay (at x=4km) and that where the delay is maximum (near x=25 km) (1). The surface between the lines is (calculate: 1 point).

(c) **Sketch the traffic situation in space-time (shock waves – no trajectories needed).** (3)
Estimate the the location of changes in traffic states.

Solution: There is a temporal blocking, so the general pattern is as follows:



(1)

The head of the queue, and thus the location of the blocking is between location 16 and 20 (1). The tail is between km 8 and 12, since there is no delay (1)

Assume a triangular fundamental diagram.

(d) **Estimate, from the given curves, give the free speed, capacity, critical density and jam density** (4)

Solution: The capacity is the derivative of cumulative curve during the outflow (0.5), here 2000 veh/h (0.5). The jam density can be derived from the number of vehicles between the cumulative curves in standstill: here 120 veh/km (480 veh in 4 km) (1). The slope of the congested branch van be determined by the speed at which the head of the queue (0.5) moves backward, e.g. at 16 km at t=0.6 and 12 km at t=0.8, i.e. 4 km in 0.2h = 20 km/h (0.5). The critical density then is the jam density minus the capacity divided by the shock wave speed (120-2000/20=120-100=20veh/km - 0.5 pt). The free speed then is the capacity divided by the critical density, i.e. 2000/20=100 km/h.

6. Crown jewels in the tower

Total for Question 6: 5

We consider an exhibition with the most important piece an object in a small glass show case in the middle of the room. Visitors do not have a preference to see a particular side of the piece. The room is 15 meters long and 6 meters wide.

(a) **Explain why a larger glass show case can increase the capacity of the exhibition room, in terms of visitors per unit of time** (2)

Solution: The limiting point for the flow is not the amount of space in the room, but the visitors watching the piece of art (1). Because then there are more visitors that can have a look at the art at the same time, because they do not stand crowded around a single object but have a large circumference to stand around (1).

An alternative design is considered. Instead of the visitors walking by the art, the visitors can stand on a moving walkway (like in the airport), which is constructed at each side of the glass. Visitors step at the moving walkway at the beginning of the room, and step off at the end. They are not allowed to walk backwards on the moving walkway.

(b) **What is the capacity of the room in this case. Base your answer on (explicitly stated) reasonable assumptions on distance and speed.** (3)

Solution: When stepping on the moving walkway, visitors keep a gross distance headway of approximately 75 cm (50-110 cm: 1 point; net=gross-20cm); assume a single lane of visitors (for the best view) per walkway. The walkway moves with an assumed 0.5 m/s (0.2-1.5: 1 point). The flow is then 1/0.75*.5=2/3 visitor per second = 40 visitors per minute. (0.5) Since there are walkways at both sides, the capacity is increased to 80 visitors per minute. (0.5)