The physical limits of buses and trains in terms of capacity

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Abstract

This paper investigates the physical limits of buses and trains in terms of capacity. In section 2, the methodological background is laid down. Two different approaches are adopted, the one for transport system requiring advanced signaling and the other for transport systems being able to run on sight. In both cases, one needs to differentiate between the line capacity and the station capacity. In section 3, a parameter study is conducted to explore the influence of different parameters and evaluate the physical limits, which still allow for stable operation. The parameter study is conducted for both trains and buses. Section 4 analyzes the effect of stations with multiple platforms. It can be shown that the line capacities of both trains and buses are in a similar order of magnitude. When considering the station capacity, the train outperforms the bus. The dwell time and thus by extension the design of vehicle plays a crucial role for capacity.

Keywords

bus, train, line capacity, station capacity, physical limits

1. Introduction

The emergence of autonomous buses will contribute to a radical change of the cost structure in the public transportation sector. The cost bloc of driver salaries, which makes up 50% to 60% of the current operating costs of buses (Brawand, 2017), will disappear and will most probably only be compensated at a much smaller extent by additional costs for dispatching, troubleshooting, maintenance or customer service. The bus thus becomes economically viable in demand ranges currently reserved to trains thanks to their better use of economies of scale (Sinner et al., 2017). Two kinds of limits determine the respective ranges where buses and trains can be operated. On the one hand, there are the economic aspects such as operating and investment cost. On the other hand, there are also the physical limits in terms of capacity, which can become limitative.

With upcoming automation, future vehicles will not necessarily look the same as current buses and trains do. The issue of generic definitions of both system has been addressed by Sinner et al. (2017). The present paper goes a step further. Based on these generic definitions, it addresses the question of what the latter imply in terms of passenger throughput and which parameters have the strongest influence.

2. Methodology

2.1 Definitions

According to Sinner et al. (2017), buses and trains can be defined as follows:

A bus is a vehicle with rubber tires, which – given its dimensions and its steering system – can be used in ordinary road traffic without geographical restriction, even if only in reduced power mode or at reduced speed (e.g. running on battery mode or using an auxiliary diesel engine).

A train is a vehicle that always needs mechanical guidance. The guidance function can be fulfilled either by the wheels or by a separate set of components.

The compatibility with ordinary road traffic required for buses implies that their vehicle length (or the platoon length since it does not matter whether vehicles are coupled mechanically or electronically) cannot be increased indefinitely. It is assumed limited to 25 m which corresponds to the length of a double-articulated bus.

For trains, one has to note that the material of the wheels it not specified in the above definition. There can both be trains with steel wheels running on steel rails or rubber-tired trains (such as certain metros or trams, for more details see Sinner et al. (2017)). The capacity calculation, however, needs to take into account the chosen material of the wheels as it determines the braking distance. While trains with steel rails cannot run on sight and thus need advanced signals for safe operation, rubber-tired vehicles could do so thanks to their significantly shorter braking distances.

The present paper will use two different methodologies to calculate the capacity limits of the trains and buses:

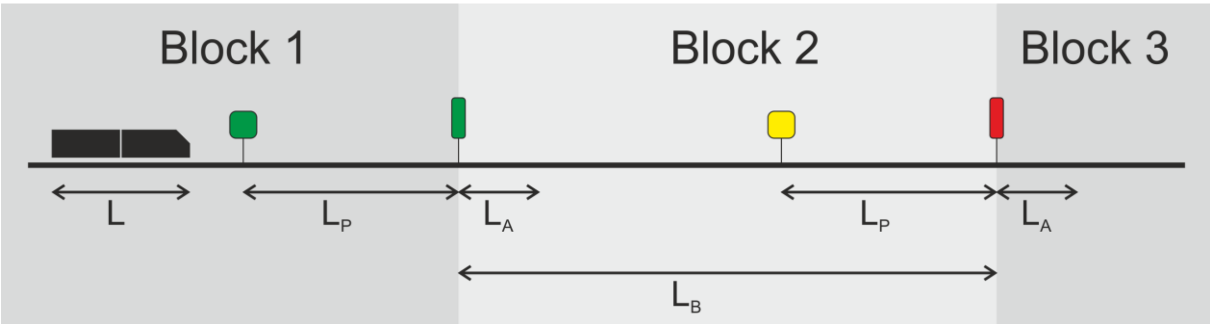
- Rail capacity: it covers systems with advanced signaling. Its main assumption is the existence of discrete section blocks, which can only be occupied by maximum one vehicle or convoy at a time.
- Road capacity: it covers systems being able to run on sight. It uses the concepts of traffic engineering. It shall also be analyzed whether this methodology is suitable for rubber-tired trains.

2.2 Rail capacity

2.2.1 Capacity of the free line without intermediate stops

The capacity of a railway line can be calculated by using the concepts of the so-called blocking staircase. It is based on the time windows a train running at operating speed needs a section block to be free to continue its journey without braking. Figure 1 shows a sequence of three section blocks. The train is allowed to enter block 2, as it is completely free. Both the advance signal and the main signal are green. Block 3, however, is assumed occupied by another train. The main signal is red, while the advance signal is yellow.

Figure 1 Schematic block representation



L is the length of the train. L_B is length of the section block. L_P is the distance between the advance signal and the main signal. L_A is the overlap.

According to Bischofberger (1997), the headway between two train can be calculated as follows:

$$t_H = \frac{L_P + L_B + L_A + L}{v} + t_S + t_R + t_{buffer} \quad (1)$$

t_S is the signal processing time, i.e. the laps of time needed for the interlocking to clear the previous slot and assign a new one. It is assumed being 10 seconds. t_R is the reaction of the driver and the mechanical engines. It is assumed being 2 seconds. The buffer time is the reserve between two train slots. It is not safety-relevant. It is a reserve built in the timetable to ensure its stability. We do not include any signal sight time, as cabin signaling (e.g. ETCS level 2) is assumed for all calculations.

The distance between the advance signal and the main signal must always be larger than the braking distance of the train. Thus:

$$L_P \geq \frac{v^2}{2a} \quad (2)$$

a is the braking performance of the train. Without loss of generality, we can say that:

$$L_B = b \cdot L_P \geq b \cdot \frac{v^2}{2a} \quad (3)$$

b is the block factor. It is the ratio between the block length and the braking distance. If b is larger than 1, we have single section signaling. The block length is larger than the breaking distance and thus the advance signal only provides information on the position of the immediately following main signal. If $b = 1$, the signals are combination signals. The main signal for block n is at the same time advance signal for block $n + 1$. If b is smaller than 1, we have multi-section signaling. The advance signal provides information for more than one block ahead. The case $b = 0$ corresponds to moving block.

In order to obtain the minimal headway, equation (1) can be reformulated as follows:

$$t_{H,line} = \frac{v}{2a} \cdot (b + 1) + \frac{L_A + L}{v} + t_S + t_R + t_{buffer} \quad (4)$$

Figure 2 Overlap length according to AB-EBV

Massgebende Einfahrgeschwindigkeit [km/h]	Mindestdurchrutschweg [m]
1 – 49	40
50 – 59	45
60 – 69	50
70 – 79	55
80 – 89	60
90 – 99	65
100 – 109	70
110 – 119	75
120 – 129	80
130 – 139	85
140 – 149	90
150 – 159	95
160	100
161 – 250	Gemäss Ziff. 4.3.4

Source: (Schweizerische Eidgenossenschaft, 2016)

The overlap L_A depends on the speed and can be calculated according to AB-EBV (see Figure 2) (Schweizerische Eidgenossenschaft, 2016). It shall be noted that the regulatory provisions in this matter are country-dependent. All subsequent calculations are made according to Swiss law.

Finally, the capacity is the inverse of the headway:

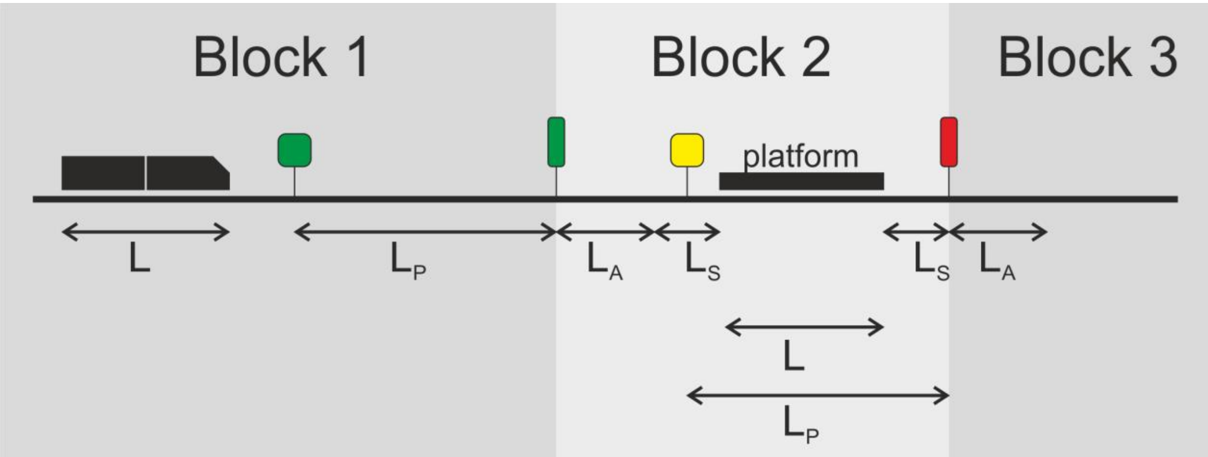
$$q_{line} = \frac{1}{t_{H,line}} \tag{5}$$

2.2.2 Capacity of a line with intermediate stops

All previous equations are based on the assumption that the train is running with constant speed and does not have intermediate stops. If there are stations within a section block, the occupation time of the respective block increases as the train needs to brake, let passengers alight and board (dwell time) and reaccelerate.

The minimum headway at a station can be obtained if the section block containing the station is as short as possible. The situation is represented in Figure 3. The length of block 2 containing the station is equal to the overlap L_A, a safety distance L_S (assumed 50 m) at each end of the platform and the length of the latter itself (assumed equal to the train length).

Figure 3 Schematic block representation



The occupation time of block 2 is the sum of the following components:

- Approach time: running time between the advance signal and the end of the platform.
- The dwell time,
- Leave time: time to reaccelerate and fully clear the block and its subsequent overlap.

Approach time

The total approach distance is $L_P + L_A + L_S + L$, of which the braking distance before reaching the end of the platform is $\frac{v^2}{2a}$. If one assumes at the same time that L_P is minimal (i.e. equal to the braking distance), the distance $L_A + L_S + L$ is left to be made at full speed v. The approach time is thus:

$$t_{approach} = \frac{L_A + L_S + L}{v} + \frac{v}{a} \tag{6}$$

Dwell time

The dwell time t_d is a parameter that needs to be chosen while taking into account various factors, including but not limited to configuration of the rolling stock, demand, design of the station, etc. (for more details see Weidmann (1994))

Leave time

For the leave time, it needs to be differentiated whether the train can reach its final speed before clearing the overlap or not.

If $L_A + L_S + L \leq \frac{v^2}{2A}$ (i.e. the train cannot reach its final speed before that point):

$$t_{leave} = \sqrt{2 \cdot A \cdot (L_A + L_S + L)} \tag{7}$$

A is the acceleration performance of the rolling stock.

If $L_A + L_S + L > \frac{v^2}{2A}$ (i.e. the train can reach its final speed before clearing the overlap):

$$t_{leave} = \frac{v}{A} + \frac{L_A + L_S + L - \frac{v^2}{2A}}{v} = \frac{v}{2A} + \frac{L_A + L_S + L}{v} \tag{8}$$

The final headway is thus

$$t_{H,station} = t_{approach} + t_d + t_{leave} + t_S + t_R + t_{buffer} \tag{9}$$

The capacity is subsequently:

$$q_{station} = \frac{1}{t_{H.station}} \tag{10}$$

2.3 Road capacity

The saturation flows in inner-city traffic for cars and buses are given by Pitzinger & Spacek (2009). They are 1800 veh/h for cars and 720 veh/h for buses on a dedicated right-of-way. Based on these values, a formula giving the saturation flow as a function of vehicle length shall be proposed. In a second step, the proposed formula shall be extended to autonomous vehicles.

2.3.1 Saturation flow as function of vehicle length

It is assumed that the considered buses were standard articulated buses. Their length is almost 19 m. The length of a car is assumed to be 5 m (Friedrich, 2015).

Based on the car following models proposed by Gipps (1981) and Mahut (2001), the following formula for the saturation flow as a function of vehicle length can be obtained when assuming stationary conditions and homogeneity among all vehicles:

$$q_{line} = \frac{1}{t_{H,line}} = \mu = \frac{1}{\tau + \frac{L_S}{v} + \frac{L}{v}} \tag{11}$$

τ is the reaction time of the driver, L_S the standstill distance and L the vehicle length. For conventional vehicles, the reaction time of the driver is assumed $\tau = 1{,}15\ s$ (Friedrich, 2015) and the standstill distance $L_S = 1{,}2\ m$ (Ambühl et al., 2016). The speed v is used as calibration parameter. Using the method of least squares, one obtains the results in Table 1. The corresponding value for v is 6,45 m/s = 23,2 km/h and the correlation coefficient is R^2 = 0,96. The speed is admittedly very low. However, the significant decrease among the measured saturation flows cannot be explained otherwise.

Table 1 Calibration of saturation flow model

Vehicle length L	$\mu_{measured}$	$\mu_{calculated}$
5 m	1800 veh/h	1705 veh/h
19 m	720 veh/h	845 veh/h

For a bus line with stops, time losses through deceleration and acceleration can be accounted for as follows[1]:

$$\Delta t_{decleration} = \Delta t_{acceleration} = \frac{v}{2a} \tag{12}$$

The flow can thus be computed as follows:

$$q_{station} = \frac{1}{t_{H,station}} = \frac{1}{t_d + 2 \cdot \frac{v}{2a} + \frac{1}{\mu}} \tag{13}$$

The expression in the denominator represents the headway. t_d is the dwell time. A potential buffer time can be considered by adding it to the dwell time.

2.3.2 Extension to autonomous vehicles

When extending the previously calibrated model to autonomous vehicles, the values of the standstill distance and the reaction time change, as vehicles can drive closer to each other and they react quicker. Accordingly, we will assume $\tau = 0{,}5\ s$ (Friedrich, 2015) and $L_S = 0{,}5\ m$ (Ambühl et al., 2016).

[1] It shall be noted that these are not the total acceleration/deceleration times. A vehicle running at constant speed also needs time to cover the acceleration/deceleration distance. The given value is only the difference.

3. Parameter study

3.1 Rail capacity

3.1.1 The influence of varying parameters

A reference case with the following parameter values is defined:

- Braking performance a = 0,8 m/s^2
- Train length L = 300 m
- No buffer time
- *For line capacity calculations:* block factor b = 1
- *For station capacity calculations:* dwell time of 60 s

In different scenarios, one parameter among the above is varied in a given range and the resulting changes in capacity are computed.

Line capacity scenarios

Table 2 summarizes the results for varying block factors. The shorter the block, the higher the capacity, since the train clears it paths in smaller portions, which can thus be reused earlier for the next train. Figure 4 holds a graphic representation of the capacity as function of speed. The different curves represent the different block factors.

Table 2 Variation of the block factor

Block factor	Capacity [trains/h]	Optimal speed
b = 0	86	81 km/h
b = 0,25	79	73 km/h
b = 0,5	74	67 km/h
b = 1	67	58 km/h
b = 2	57	47 km/h

Table 3 Variation of train length

Train length	Capacity [trains/h]	Optimal speed
L = 100 m	94	38 km/h
L = 200 m	77	48 km/h
L = 300 m	67	58 km/h
L = 400 m	60	66 km/h
L = 500 m	56	73 km/h

Table 3 summarizes the results for changes in train length. The shorter the train, the higher the capacity and the lower the optimal speed. With longer trains, the optimal speed is higher as the part of the time needed for clearing the block and the overlap grows more important. Overall, it is more efficient to run longer trains, as the loss in terms of slots due to the greater length is outweighed by far by the additional load capacity of each single train.

Figure 4 Capacity as function of speed with varying block factors

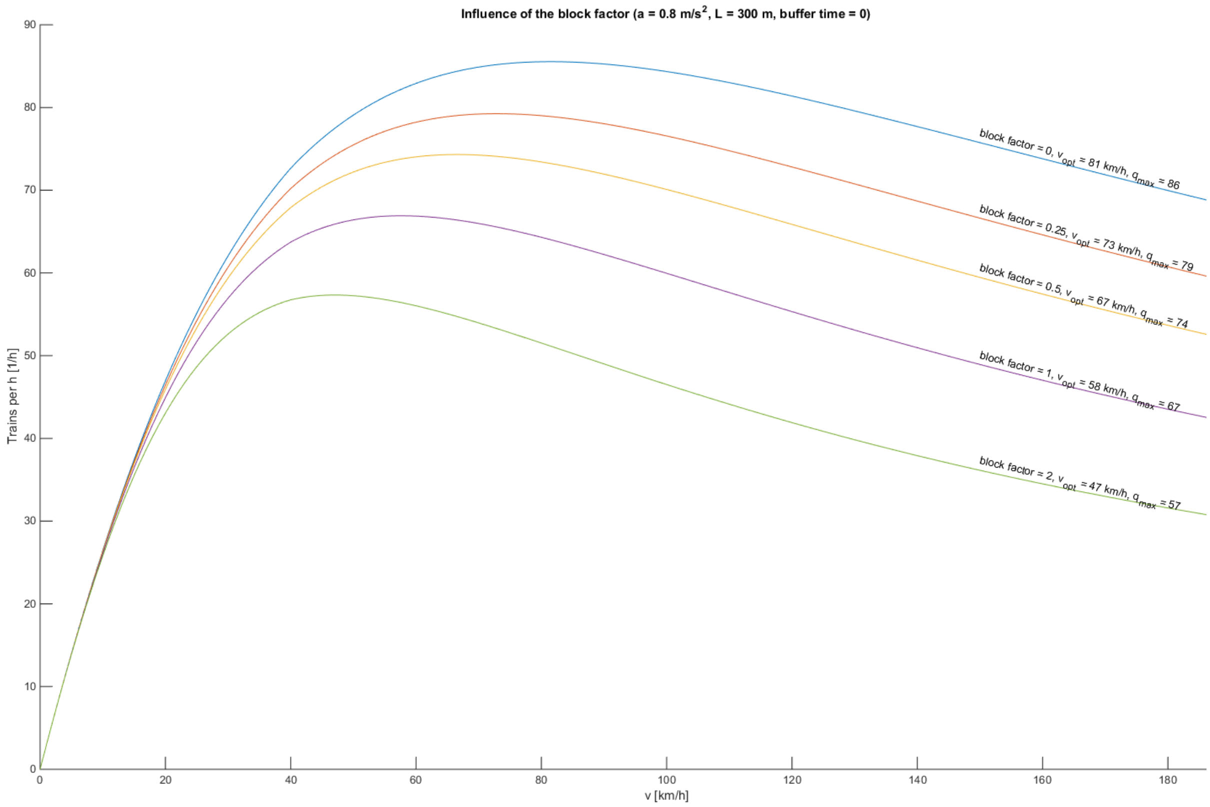


Table 4 Variation of the buffer time

Buffer time	Capacity [trains/h]	Optimal speed
0 s	67	58 km/h
10 s	56	58 km/h
20 s	49	58 km/h
30 s	43	58 km/h
40 s	38	58 km/h
50 s	35	58 km/h
60 s	32	58 km/h

Table 5 Variation of braking performance

Braking performance	Capacity [trains/h]	Optimal speed
1,2 m/s^2	77	71 km/h
1,1 m/s^2	75	68 km/h
1,0 m/s^2	73	64 km/h
0,9 m/s^2	70	61 km/h
0,8 m/s^2	67	58 km/h
0,7 m/s^2	64	54 km/h
0,6 m/s^2	60	50 km/h
0,5 m/s^2	56	46 km/h

Table 4 provides the results for varying buffer times. We notice that the optimal speed does not change, since the buffer time enters as a constant term into the headway equation (4). Table 5 finally provides the results for varying braking performance. As one can expect, with higher braking power, the capacity increases as the distance between advance and main signal can be shortened. With higher braking performance, the optimal speed also increases. Trains braking and accelerating faster are thus both beneficial for infrastructure capacity and travel times.

Station capacity scenarios

The tables below summarize the results for the station capacity scenarios. It can be noted the degree of variability is smaller than for the line capacity.

Table 6 Variation of dwell time

Dwell time	Capacity [trains/h]	Optimal speed
30 s	29	69 km/h
45 s	26	69 km/h
60 s	24	69 km/h
75 s	21	69 km/h
90 s	20	69 km/h
105 s	18	69 km/h
120 s	17	69 km/h

Table 7 Variation of train length

Train length	Capacity [trains/h]	Optimal speed
L = 100 m	28	47 km/h
L = 200 m	25	59 km/h
L = 300 m	24	69 km/h
L = 400 m	22	77 km/h
L = 500 m	21	85 km/h

Table 8 Variation of the buffer time

Buffer time	Capacity [trains/h]	Optimal speed
0 s	24	69 km/h
10 s	22	69 km/h
20 s	21	69 km/h
30 s	20	69 km/h
40 s	19	69 km/h
50 s	18	69 km/h
60 s	17	69 km/h

Table 9 Variation of braking performance

Braking performance	Capacity [trains/h]	Optimal speed
1,2 m/s^2	26	84 km/h
1,1 m/s^2	25	81 km/h
1,0 m/s^2	25	77 km/h
0,9 m/s^2	24	73 km/h
0,8 m/s^2	24	69 km/h
0,7 m/s^2	23	64 km/h
0,6 m/s^2	22	60 km/h
0,5 m/s^2	21	54 km/h

It is assumed that the acceleration performance A is equal to 80% of the braking performance. In general, the braking performance would be much higher than the acceleration performance. However, for comfort and passenger safety reasons, full braking performance is not used in regular operation but only in emergency cases (Filipović, 2015; Weidmann, 2011).

The number of slots is in general between 20 and 30 per hour. Buffer time and dwell time act in the same way on the final capacity: they are both constant terms of the headway equation (9). Thus, they do not influence the optimal speed.

3.1.2 The system limits

In this section, we will analyze how far capacity can be pushed when combining the factors in the most positive possible combination, which is technically feasible and realistic in terms of operational requirements. The train length will be considered as a varying factor.

Two scenarios for conventional and automated trains respectively are defined as specified in Table 10. They are only differ by the assumed buffer time. Automated trains can run much more precisely than conventional trains controlled by a human driver. Thus, the buffer time can be reduced for the former. The assumed braking performance is what can be reached by modern commuter trains rolling stock (Filipović, 2015). The block factor of 0,25 corresponds to the technical possibilities under continuous cabin signaling systems such as LZB or ETCS level 2. The dwell time of 30 s is rather short but can be achieved if the rolling stock has enough doors like modern metros do.

Table 10 Parameters for system limits scenarios

Parameter	**Scenario conventional train**	**Scenario automated train**
Braking performance	a = 1,2 m/s^2	a = 1,2 m/s^2
Buffer time	**t_{buffer} = 30 s**	**t_{buffer} = 10 s**
Block factor	b = 0,25	b = 0,25
Dwell time	t_d = 30 s	t_d = 30 s

Line capacity

The line capacity for the two scenarios explained before is given in Table 11. We notice that the reduction of buffer time from 30 s to 10 s leads to a capacity increase of up to 50 %. In addition, one can see that the capacity in terms of number of slots is the highest for short trains. However, when considering the actual load capacity (i.e. the train volume available for transporting passengers or cargo), the longer trains outperform the shorter ones by far. Figure 5 and Figure 6 show the graphical representations of the aforementioned results as a function of speed. In practice, these capacities could only be reached on very small sections without any station. Additionally, trains would have to line up very precisely at the entry to such a high-density section.

Table 11 System limits of line capacity

Train length	Conventional operation		Automated operation	
	trains/h	train-m/h	trains/h	train-m/h
L = 100 m	60	6’000 m	91	9’100 m
L = 200 m	55	11’000 m	80	16’000 m
L = 300 m	52	16’000 m	73	22’000 m
L = 400 m	49	20’000 m	67	27’000 m
L = 500 m	47	**23’000 m**	63	**32’000 m**

Figure 5 Maximum line capacity for conventional trains

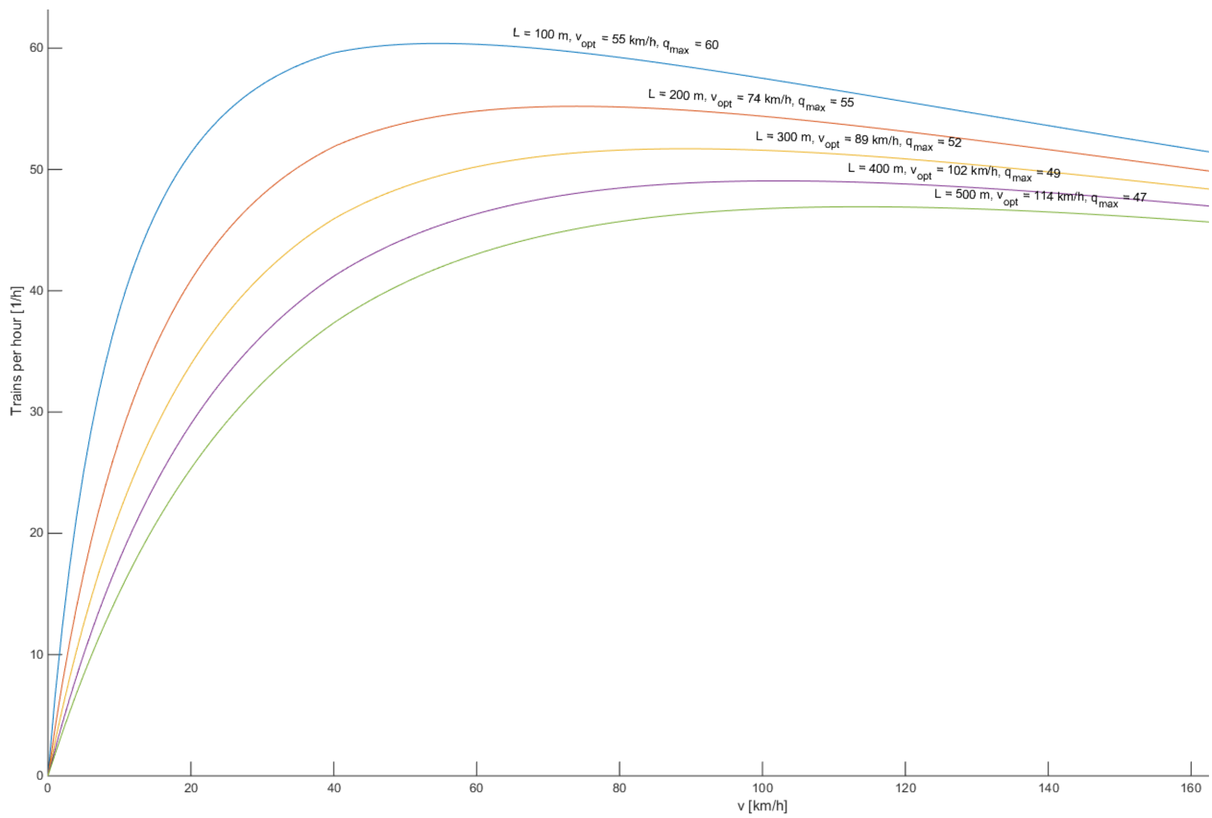
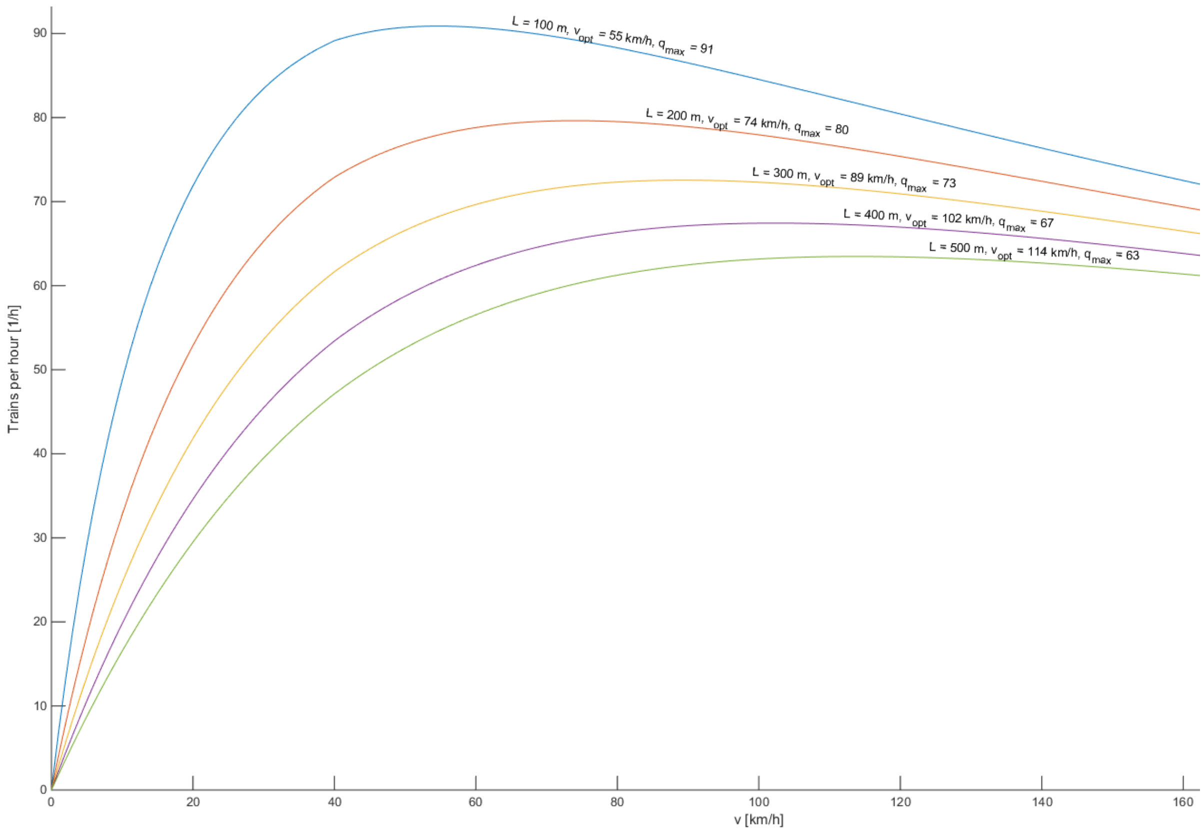


Figure 6 Maximum line capacity for automated trains



Station capacity

The station capacity has greater practical relevance than the line capacity. It can be observed in reality on lines where rolling stock and service patterns are fully homogenous, i.e. on suburban railway lines and metros. The results are summarized in Table 12. Figure 7 und Figure 8 provide the graphical representations.

These results can be compared to what has been realized in practice. The S-Bahn Munich runs on its central section between München Hbf and Ostbahnhof with a frequency of 24 trains per hour. This corresponds to the order of magnitude of the system limits in conventional operation (including buffer time of 30 s). The technical limit that can be observed on that particular section is a headway of 96 s (which corresponds to 37 trains per hour) (Weidmann, 2014). It is important to note that this technical limit does not include buffer time. The buffer time is not safety relevant but is only taken into account for the purpose of operational stability.

On the London underground, the recent upgrade of the Circle, District, Hammersmith & City and Metropolitan lines (the so-called sub-surface lines) with Communication Based Train Control (CTBT) and Automatic Train Operation (ATO) allowed service frequency to be increased from 24 to 32 trains per hour (EuroTransport, 2016). Again, the order of magnitude matches very well with the results of Table 12. CTBT is a technology that implements moving blocks. However, for stations, the block length does have a large influence, as the dwell time is the dominating parameter.

Table 12 System limits of station capacity

Train length	Conventional operation		Automated operation	
	trains/h	train-m/h	trains/h	train-m/h
L = 100 m	30	3’000 m	37	3’700 m
L = 200 m	28	5’600 m	33	6’600 m
L = 300 m	26	7’800 m	30	9’100 m
L = 400 m	24	9’800 m	28	11’000 m
L = 500 m	23	**12’000 m**	27	**13’000 m**

Figure 7 Maximum station capacity for conventional trains

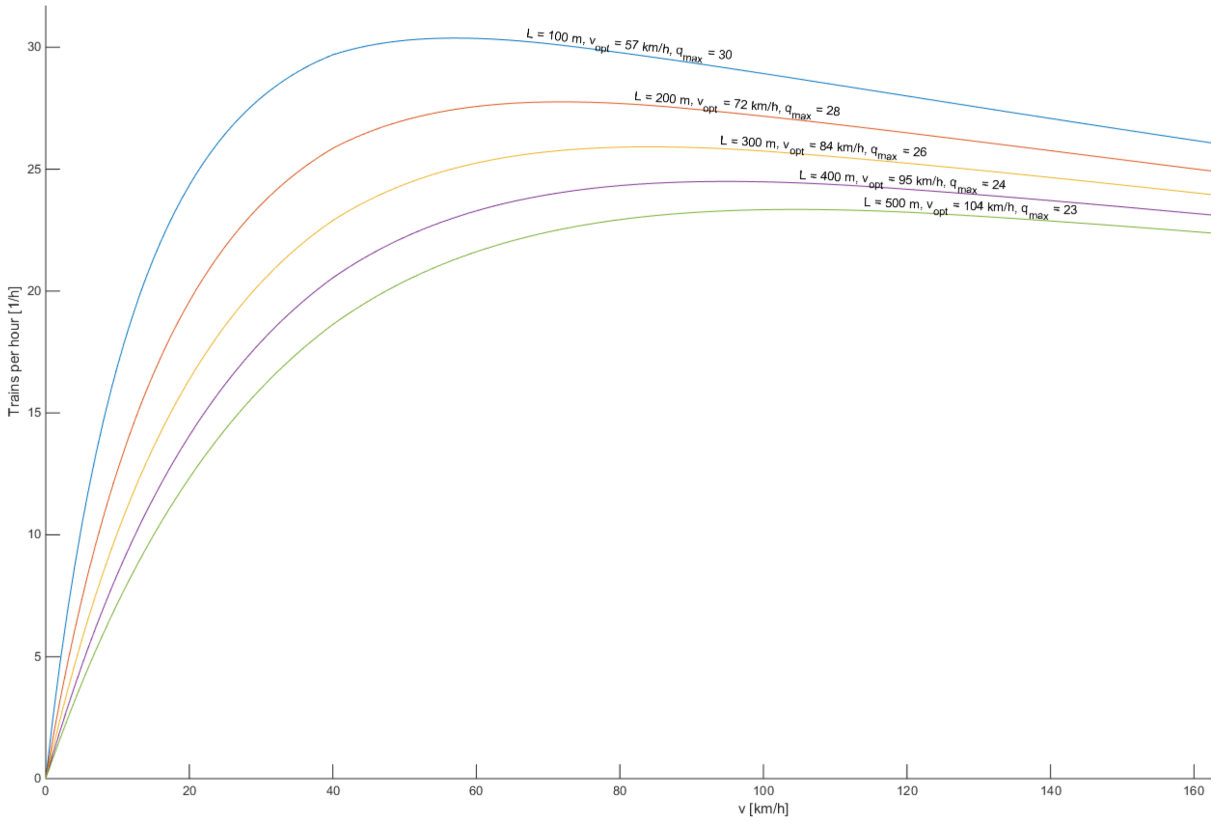
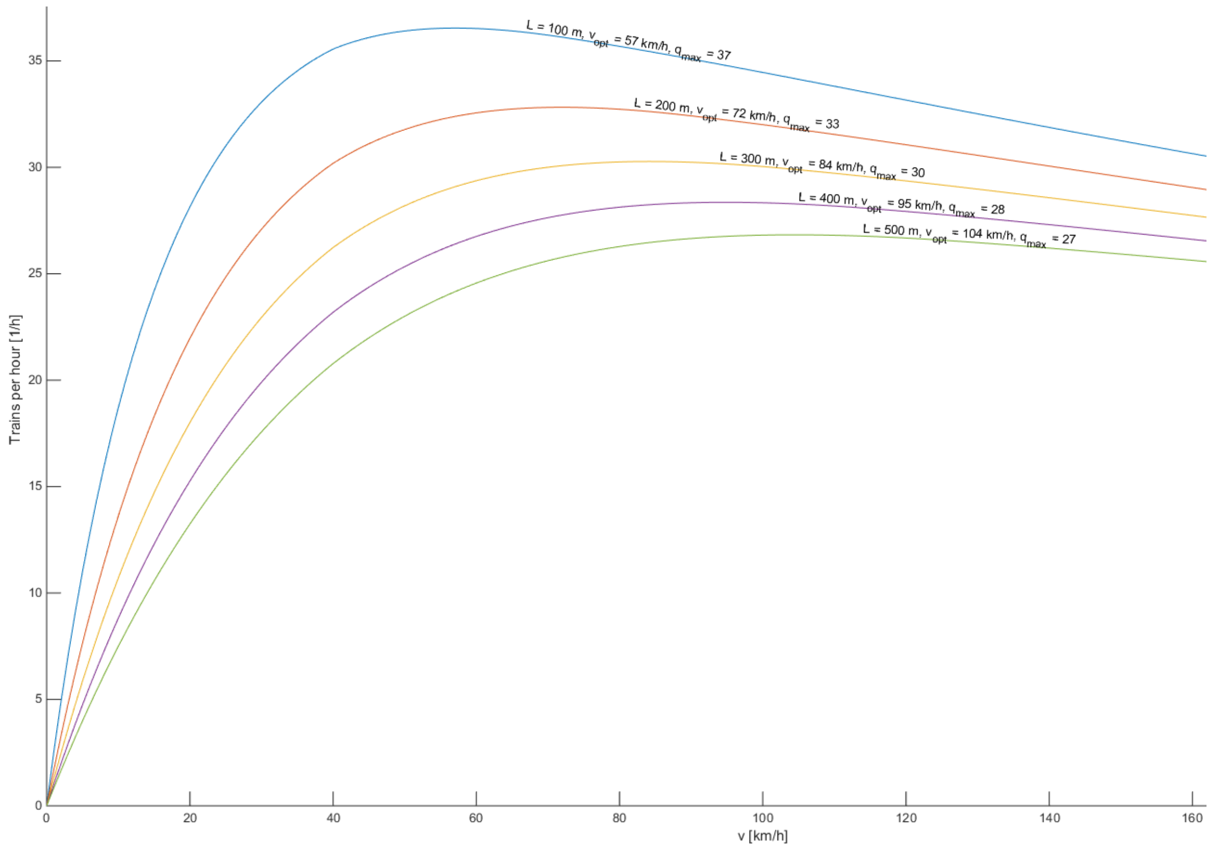


Figure 8 Maximum station capacity for automated trains



3.2 Road capacity

Using equations (11) and (13), the maximum flow can be computed as a function of vehicle length and dwell time (see Figure 9). A buffer time of 10 seconds is assumed for all subsequent computations. The acceleration and deceleration performance is assumed 1,5 m/s^2. Although buses and road vehicles in general are capable of much higher rates, they are avoided for comfort and passenger safety reasons. One can notice that even with small dwell times of 10s (which admittedly are very unrealistic for practice) the resulting flow is significantly reduced compared to the saturation flow.

Figure 10 shows the same data for autonomous vehicles (see section 2 for information on how they differ from conventional vehicles). While the saturation flow of a stream without stop increases in a significant way, the flows for streams with stops do not change much.

Figure 9 Flows for conventional vehicles

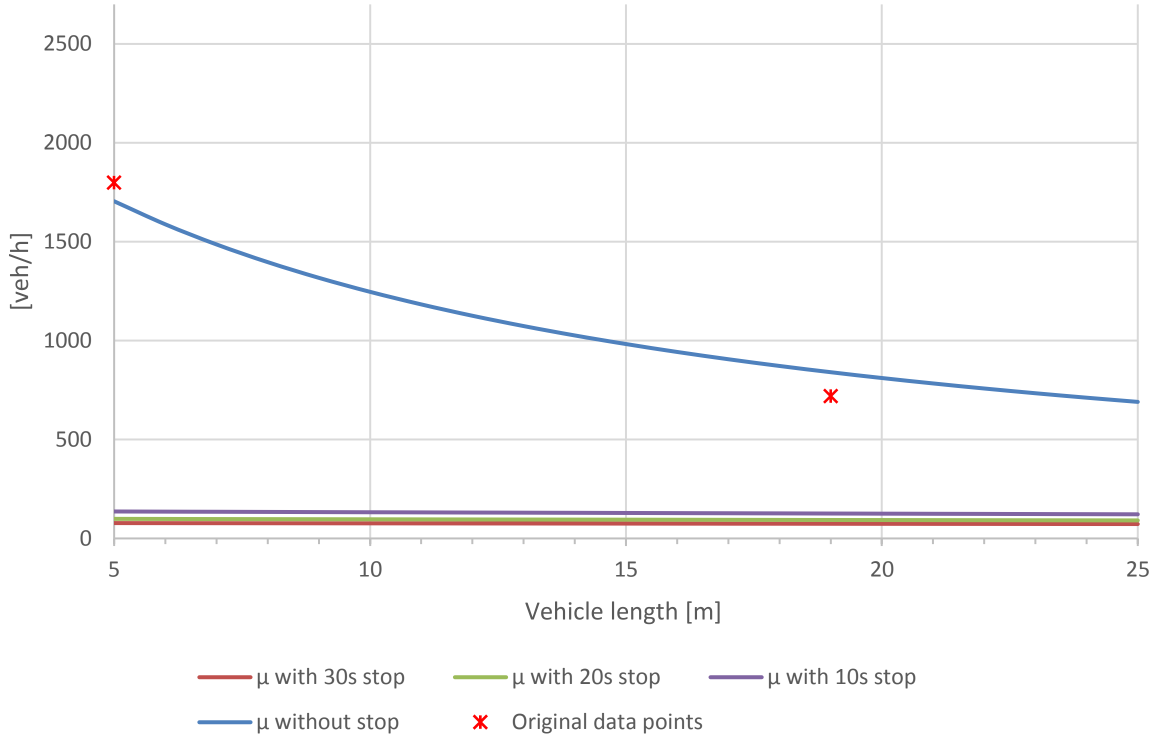


Figure 10 Flows for autonomous vehicles

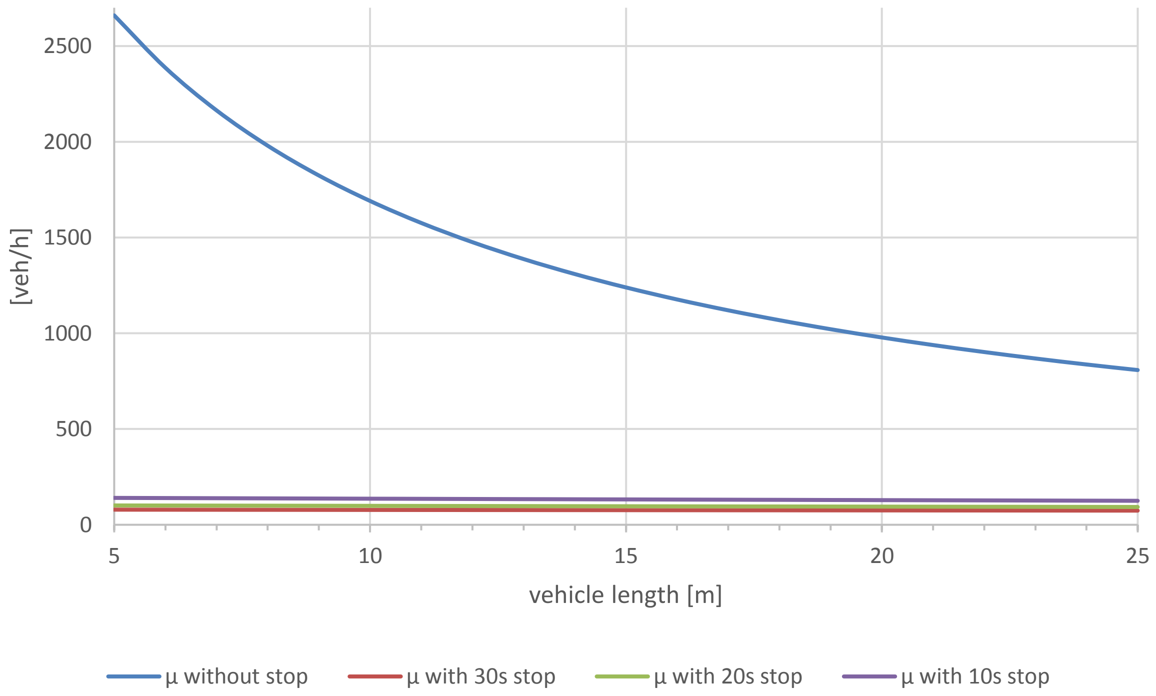


Table 13 Flows depending on stop time

Vehicle length	Conventional vehicles – flow in veh/h			Autonomous vehicles – flow in veh/h		
	10 s stop	20 s stop	30 s stop	10 s stop	20 s stop	30 s stop
5 m	136	99	78	140	101	79
12 m	131	96	76	135	98	77
19 m	126	93	74	129	95	75
25 m	122	91	73	125	93	74

Table 13 summarizes the flows for streams with intermediate stops for chosen vehicle lengths and stop times: 5 m car, 12 m standard bus, 19 m articulated bus and 25 double-articulated bus. [2]One recognizes that the results do depend very little on the length. On the other hand, the stop time has a far greater influence. Furthermore, the effect of automation is very limited, as its main advantages cannot be used.

As mentioned previously, it shall be analyzed whether rubber-tired trains could be regarded as very long buses. Table 14 summarizes the achievable vehicle throughput if vehicle lengths up to 500 m are considered. Stop time (where applicable) is 30 s.

It can be seen that the saturation flow drops significantly with increasing vehicle length. The $\frac{L}{v}$ term in the saturation flow equation (11) gets dominating. Since the speed that resulted from the calibration is comparably low, the time to move forward by the own vehicle length becomes extremely large. Modelling capacity of rubber-tired trains with the concepts of road traffic thus does not prove suitable. They should rather be modelled with the concepts of rail while taking into account higher braking and acceleration performances (within the limits of passenger comfort and safety).

For buses, where compatibility with road traffic is required and vehicle length is limited to 25 m, the achievable throughput with stop time of 30 s (and 10 s buffer time) and autonomous vehicles is 74 veh/h or 1850 veh-m/h.

[2] The headways corresponding to these flows are only feasible on a dedicated right-of-way. Under mixed traffic conditions, they cannot be operated reliably. The phenomenon in German called “Störungsaufschaukelung” (a small initial deviation from schedule leading to bus bunching, for more details see Weidmann (1994)) cannot happen, as vehicles already run in a bunched way.

Table 14 Flows depending on vehicle lengths

Vehicle length	Conventional vehicles				Autonomous vehicles			
	No stop		*30 s stop*		*No stop*		*30 s stop*	
	veh/h	veh-m/h	veh/h	veh-m/h	veh/h	veh-m/h	veh/h	veh-m/h
12 m	1126	13’512	76	912	1476	17’712	77	924
19 m	840	15’960	74	1’406	1021	19’399	75	1’425
25 m	690	**17’250**	73	**1’825**	808	**20’200**	74	**1’850**
100 m	214	21’400	59	5’900	224	22’400	60	6’000
200 m	111	22’200	47	9’400	114	22’800	47	9’400
300 m	75	22’500	39	11’700	76	22’800	39	11’700
400 m	57	22’800	33	13’200	57	22’800	34	13’600
500 m	46	**23’000**	29	**14’500**	46	**23’000**	29	**14’500**

3.3 Comparison Rail vs Road

If one compares the achievable throughputs of both calculation methodologies (see Table 15), it becomes evident that rail can offer much higher capacities than buses. The difference is particularly large when having intermediate stops. This is primarily because the dwell times of all single vehicles are summed up. For buses, the platform occupation time is the limiting factor. In the following chapter, we will explain how these deficiencies can be eased when considering stations with multiple platforms or bus bays.

Table 15 Comparison Rail vs Road

Vehicle type	Conventional vehicles flow in veh-m/h		Autonomous or automated vehicles – flow in veh-m/h	
	No stop	30 s stop	No stop	30 s stop
Rail	23’000	12’000	32’000	13’000
Bus	17’250	1’825	20’200	1’850

4. Stations with multiple platforms

All previous calculations with intermediate stops assumed the presence of only one platform track / bay per line track / lane. That way, it becomes imperative that the station is the limiting factor of the line. With multiple platforms, however, the capacity can be further increased (in some situations such that the line becomes the limiting factor).

In principle, three different configurations are possible:

1. Parallel setting
2. Serial setting
3. A combination of the two above

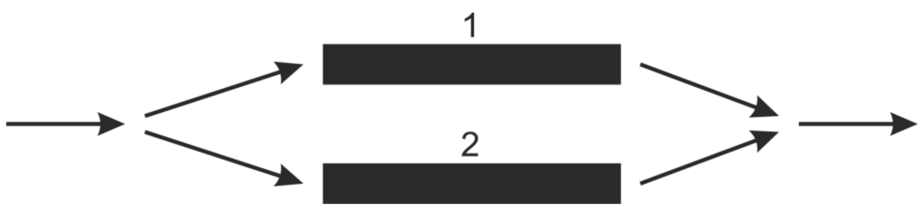
The serial setting, however, is of limited utility in this context. Once a vehicle has arrived in the most upstream bay, the following vehicle can only arrive when the former has cleared its position, since surpassing is not possible. The serial setting alone thus always yields the same capacity as a single bay.

It is assumed for all these calculations, that vehicles are regularly spaced in time.

4.1 Parallel configuration

Figure 11 shows the principle of the parallel setting. Both platforms are occupied in alternation.

Figure 11 Parallel platform configuration



Let n be the number of platforms. If $t_{H,station}$ is the headway for a single-platform-station and $t_{H,line}$ is the headway for the free line, then the maximum headway for a multi-platform-station with n platforms is:

$$t_H(n \text{ platforms}) = max\left(\frac{t_{H,station}}{n}, t_{H,line}\right) \tag{14}$$

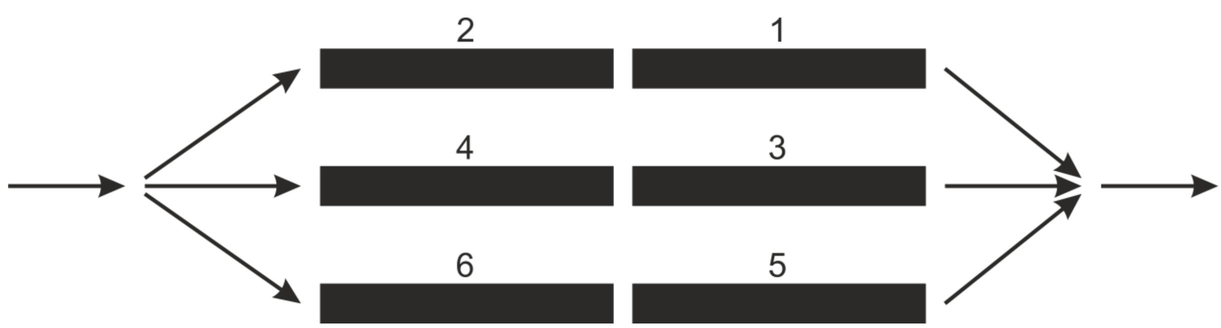
Naturally, the headway can never be smaller than the headway of the line, as the technical parameters of the latter did not change. The line capacity works as a cap. If we transform this equation (14) into flows, we obtain:

$$q(n \text{ platforms}) = min(n \cdot q_{station}, q_{line}) \quad (15)$$

4.2 Parallel & serial configuration

When adopting a combined parallel and serial configuration, the platforms are occupied in the order shown in Figure 12. Let n be the number of parallel platforms and m the number of serial platforms. In the example shown in Figure 12, n is 3 and m is 2.

Figure 12 Parallel platform configuration



In this case, headway and capacity are given by the following equations:

$$t_H(n \cdot m \text{ platforms}) = max\left(\frac{t_{H,station}}{n \cdot m}, t_{H,line}\right) \quad (16)$$

$$q(n \cdot m \text{ platforms}) = min(n \cdot m \cdot q_{station}, q_{line}) \quad (17)$$

However, a very important side constraint needs to be respected. In the example shown in Figure 12, the train or bus stopping at platform 5 can only enter once the one having stopped at platform 6 has left. This condition is expressed by the following equation:

$$t_H(n \cdot m \text{ platforms}) \cdot (n \cdot m - m + 1) \geq t_{H,station} \quad (18)$$

If we put in equation (18) $n = 1$ (i.e. a purely serial configuration), we would obtain:

$$t_H(1 \cdot m \text{ platforms}) \cdot (m - m + 1) \geq t_{H,station}$$
$$\Leftrightarrow t_H(m \text{ platforms}) \geq t_{H,station} \quad (19)$$

The headway of a purely serial configuration is thus also the same as for a single platform (under the assumption that vehicles run in a regularly spaced way).

4.3 Application to physical system limits

Using the formulas above, one can compute the number of platforms that is required in order to use the full line capacity. Table 16 summarizes the results for one type of bus and train respectively. One can see that the number of platforms (or bays) is much larger for buses than for trains.

Table 16 Number of platforms to use line capacity

		Maximum line capacity [veh/h]	**Maximum station capacity** [veh/h] (t_d = 30 s)	**Required platforms or bays to use line capacity**	
				exact	**rounded**
Train L = 300 m	Conventional	52	26	*2,0*	**2**
	Automated	73	30	*2,4*	**3**
Bus L = 19 m	Conventional	840	74	*11,4*	**12**
	Autonomous	1021	75	*13,6*	**14**

Furthermore, one should bear in mind that the above results heavily depend on the assumed dwell time. With increasing dwell time, the number of platforms or bays increases as well. The station capacity will be the limiting factor when applying autonomous driving to high capacity public transportation.

Lutin & Kornhauser (2014) propose to use autonomous driving technology to increase the capacity of bus services between New Jersey and New York City. In different scenarios, they assume headways between 1s and 5s to evaluate the resulting passenger capacity. However, they do not consider the stations and in particular the one of the assumed bus terminal in New York City where services would end. It can be assumed that all passengers alight or board there. In that case, the dwell time is probably even higher than the 30s used in Table 16, which again drives up the required number of bus bays.

Hence, the vehicle configuration (number of doors, etc.) will be an essential factor to take into account when implementing autonomous driving. Only with short dwell times, the benefits of the latter can be utilized in high capacity public transport.

5. Conclusion

This paper investigated the physical limits of buses and trains in terms of capacity. The key findings are the following:

1. Both systems can provide capacities in comparable orders of magnitude in terms of vehicle-m per hour if they operate on the free line without intermediate stops (15'000 – 20'000 veh-m/h). Assuming a passenger density of 8 passengers per veh-m (average value for buses and trains by Anderhub et al. (2008) [3]), their capacity would be 120'000 – 160'000 passengers per hour. This is much more than the demand of public transport lines.

2. When considering intermediate stops, rail can provide much higher throughputs thanks to the larger vehicle length (around 5 to 6 times more capacity depending on the vehicle lengths used). While rail can provide throughputs of ca. 10'000 veh-m/h (i.e. ca. 80'000 passenger/h), the bus is limited to 1500 – 1800 veh-m/h (i.e. 12'000 – 14'400 passenger/h). Although the difference between both is significant, the demand on Swiss public transport lines is in general below the capacity limit of the bus. It shall however be reminded, that these bus capacities require a fully separated right-of-way without traffic lights.

3. Thanks to multiple platforms at stations, the capacity of the latter can be increased to make better usage of the line capacity. However, this needs additional space (more land or larger underground caverns as parallel setting of platforms is required) which involves higher infrastructure cost.

4. Longer vehicles are always preferable. Their additional length always outweighs by far the capacity loss due to their increased length.

5. The influence of dwell times on station throughputs and thus also on line throughputs shows that vehicle properties (number of doors, etc.) must be taken into account.

[3] The passenger/veh-m value depends on the one hand on the required level of service (LOS) and on the other hand on the allowable width of the vehicle. For instance, trains running on the Russian broad gauge (1520 mm) network (including some countries in Eastern Europe) enjoy a much wider clearance diagram than those running in Western and Central Europe (1435 mm normal gauge). Metros often have their very specific clearance requirements and a general statement is thus not possible.

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