INFLUENCE OF MODIFIED POWERTRAIN MASSES ON THE RIDE COMFORT OF A LIGHT RAIL VEHICLE

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ABSTRACT

Lower powertrain masses and new integration possibilities can be accomplished by using high-speed machines. Since a changed powertrain means a change of the overall system, the aim of this paper is to examine the effects on the system property passenger comfort. This is done using a simulative approach. First, a multi-body model of a Flexity Zurich, a low-floor vehicle that has been operating in Zurich since 2020, is created using the software Simpack. Subsequently, a run on line 9 is simulated and evaluated according to common methods for determining the passenger comfort of rail vehicles. In detail, these are the Sperling method and the Continuous Comfort method according to DIN EN 12299. In order to investigate how powertrains with high-speed machines affect passenger comfort, the model is modified. Machines and gearboxes are replaced by new components that lead to a significant reduction in the mass of the powertrain. It is shown that a concept that leads to a 13% reduction in the primary suspended mass does not have any significant impact on passenger comfort in the simulated vehicle on the specified route. Neither does a concept that leads to a 35% reduction in primary suspended mass and a 38% increase in unsprung mass. In order to gain an insight into the influence of the unsprung and primary suspended mass on passenger comfort, a series of simulations are carried out to investigate this relationship on a broadband basis on the above vehicle. The results show that there is no evidence of a correlation between the unsprung and primary suspended masses and passenger comfort in the lateral direction. However, there is a slight trend towards better comfort values in the vertical direction with lower unsprung and primary suspended masses.

Keywords: comfort, unsprung, primary suspended, powertrain, mass, light rail, tram.

1 INTRODUCTION

Public transport operators want to shift the modal split in favour of their modes of transport. To achieve this in the light rail sector, the vehicles must meet certain requirements. These include the use of energy efficient powertrains as well as providing a high passenger comfort [1].

Powertrains with high-speed machines can contribute to this, as they promise higher efficiency and thus lower energy consumption compared to conventional machines. This leads to lower operating costs. Furthermore, powertrains with high-speed machines can be realised smaller and lighter than conventional machines [2].

Heckele et al. [3] investigate how much energy can be saved if a Flexity Zurich, a low floor tram operating in Zurich, is equipped with a powertrain with high-speed machines. They show that energy consumption can be reduced by up to 29% to 3.5 kWh/km. According to the authors, this is due to both the 21% reduction in powertrain mass and the use of components which lead to an increase in powertrain efficiency of 9 percentage points to 84%.

The mass of a railway vehicle can influence the vibrations of railway vehicles [4]. Therefore, we expect that the passenger comfort will also be influenced. The aim of this paper is to investigate the extent of this influence in order to assess whether mass reduction through high-speed machines can contribute to higher passenger comfort. To the authors' knowledge, there are no publications thus far that have investigated this relation.

In order to determine this, a simulative approach is taken. In the field of rail vehicles, simulations are commonly used as an analytical investigation of the behaviour of entire

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vehicles is not possible. Therefore, multi-body simulation software is used to assess the dynamic behaviour [5].

On the one hand, manufacturers use multi-body simulation to meet safety criteria such as protecting the vehicle from derailing or overturning. On the other hand, it can be used to ensure that freight and passengers are not exposed to unacceptable vibrations, i.e., to guarantee sufficient comfort [6].

We create a multi-body model of the Flexity Zurich using the software Simpack. Different configurations of this model are subjected to a run on the line 9 and are evaluated according to common methods for assessing passenger comfort.

In Haladin et al. [7], various methods for determining passenger comfort in rail vehicles were investigated for their suitability in light rail vehicles. The authors conclude that the Sperling method is convenient for assessing tramway infrastructure and ride comfort. However, they criticize that it cannot evaluate comfort in longitudinal direction, although recurring start–stop driving is of great importance for ride comfort. Furthermore, they reckon the valid frequency range to be not sufficient to properly reflect excitations caused by welding irregularities. They also examined the methods provided by EN 12299 for determining passenger comfort in rail vehicles. The Mean Comfort methods are not suitable for light rail vehicles as the standard demands 5-minute-long test sections with constant speed which is too long for light rail track sections. Nonetheless, the authors consider the Continuous Comfort method suitable as vibration levels are averaged over five seconds, and it provides a sufficient valid frequency range up to 100 Hz. They cite the resolution of the scale as a disadvantage of this method. In their measurement, 95% of all comfort values already fall in the highest comfort category which makes it inconvenient to compare different test sections to one another [7].

In this paper, we use both the Sperling method and the Continuous Comfort method to evaluate the different configurations of the model to obtain findings about the influence of powertrain masses on the passenger comfort.

2 METHODS FOR DETERMINING PASSENGER COMFORT

The most common methods to determine passenger comfort of rail vehicles in general are:

1. the Sperling method; and
2. the methods according to EN 12299, which is based on ISO 2631 [6].

Each of which were originally developed for the heavy rail sector, but according to Haladin et al. [7], both the Sperling method and the Continuous Comfort method in EN 12299 are suitable for the light rail sector. In the following, a brief overview of the mentioned methods will be given. Both methods consider the accelerations and frequencies a human is exposed to as the only relevant factors for comfort.

2.1 Sperling method

Sperling developed a method for evaluating the ride quality of passenger and freight wagons [8], [9]. In this method, a ride index Wz, which describes the comfort, is calculated using eqn (1):

$$Wz = \sqrt[10]{B(f)^3 \hat{a}^3}. \tag{1}$$

This is an empirically established correlation between the ride index Wz and a perceived excitation with the acceleration amplitude $\hat{a}$ in $\mathrm{m/s^2}$ and the frequency f in Hz. In $B(f)$, the frequency is weighted to consider that humans perceive different frequencies differently.

$B(f)$ is valid in a frequency range from 0.5 Hz to 20 Hz and is calculated as follows for the lateral and vertical direction:

$$B_{\text{vert}}(f) = 0.588\sqrt{\frac{1.911f^2+(0.25f^2)^2}{(1-0.277f^2)^2+(1.563f-0.0368f^3)^2}}, \tag{2}$$

$$B_{\text{lat}}(f) = 1.25 \cdot B_{\text{vert}}(f). \tag{3}$$

There is no weighting curve for the longitudinal direction [10].

The lower the ride index Wz, the better the comfort. Table 1 shows which ride index corresponds to which perception.

Table 1: Ride index evaluation scale [10].

Wz	Description in words
1	Just noticeable
2	Clearly noticeable
2.5	More pronounced but not unpleasant
3	Strong, irregular, but still tolerable
3.25	Very irregular
3.5	Extremely irregular, unpleasant, annoying; prolonged exposure intolerable
4	Extremely unpleasant; prolonged exposure harmful

Eqn (1) is only valid for accelerations with a single frequency. Since in reality accelerations occur with multiple frequencies, the whole spectrum must be considered. This is done with eqn (4) [6]:

$$Wz = \left[2\sum_{i=1}^{n}\left(B(f_i)a_{i,\text{RMS}}\right)^2\right]^{0.15}, \tag{4}$$

with

$$a_{\text{RMS}} = \sqrt{\frac{1}{2}\hat{a}^2}. \tag{5}$$

2.2 Continuous Comfort according to EN 12299

This method uses the time-dependent accelerations a to determine the Continuous Comfort C_{C}. Depending on the direction, the values are calculated according to the following equations:

$$C_{\text{Cx}}(t) = a_{\text{XP}}^{\text{W}_\text{d}}(t), \tag{6}$$

$$C_{\text{Cy}}(t) = a_{\text{YP}}^{\text{W}_\text{d}}(t), \tag{7}$$

$$C_{\text{Cz}}(t) = a_{\text{ZP}}^{\text{W}_\text{b}}(t). \tag{8}$$

The accelerations are RMS values averaged over 5 seconds. W_d and W_b refer to weighting curves in a frequency range between 0.1 Hz and 100 Hz. P indicates the location where the measurement is made, in this case on the floor. The calculated values for $C_{\text{Cy}}(t)$ and $C_{\text{Cz}}(t)$ can be classified on the evaluation scale shown in Table 2.

However, this evaluation scale is only preliminary, and the standard does not provide a scale for $C_{\text{Cx}}(t)$ thus far [11].

Table 2: Evaluation scale for C_{Cy} and C_{Cz} [11].

$C_{\mathrm{Cy}}(t)$, $C_{\mathrm{Cz}}(t)$ in $\frac{m}{s^2}$	Description in words
<0.2	Very comfortable
0.2–0.3	Comfortable
0.3–0.4	Medium
>0.4	Less comfortable

3 SIMULATION OF PASSENGER COMFORT

This section presents the models of the chosen track and vehicle. Next to the baseline, the changes made on it are explained.

3.1 Track

The track the vehicle is simulated on is the tramline 9 in Zurich. A cartographic track is created with the track and height profile shown in Fig. 1. *x*, *y* and *z* are spatial coordinates and *s* refers to the length of the track.

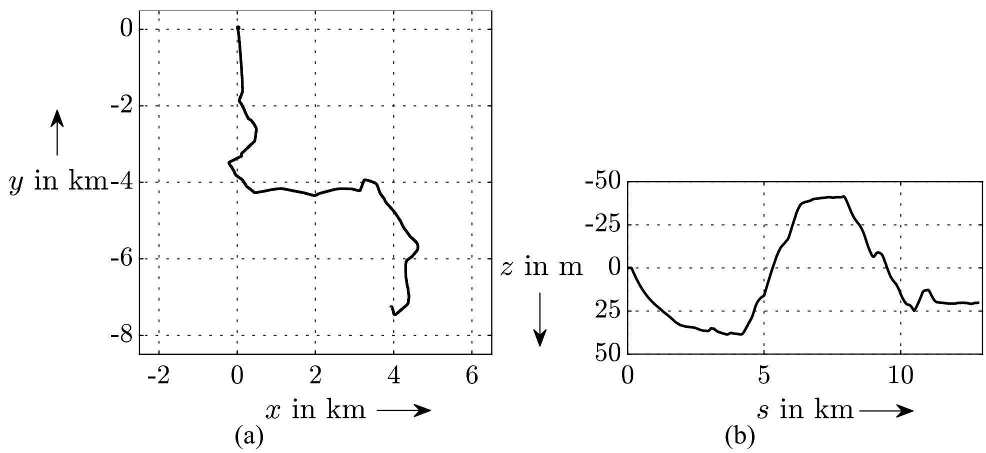

Figure 1: (a) Track profile; and (b) Height profile.

In accordance with the official planning guideline [12], superelevation is added. Furthermore, track irregularities are added as these are mainly responsible for the excitation of a rail vehicle [6]. These irregularities are modelled small according to [13].

3.2 Vehicle configurations

Subsequently, the multi-body model of the Flexity Zurich created in Simpack is presented. Furthermore, the mass-related changes that are made to the vehicle are explained.

3.2.1 Baseline

Fig. 2 shows the model of the topology of the model of the Flexity Zurich. It is based on dimensions and mass properties available to the authors as well as the spring and damper constants of the force elements. The cars 1, 3, 5 and 7 have bogies, all of which are powered expect for car 3. Each bogie consists of two wheelsets which have a force element that models the wheel–rail contact based on FASTSIM. The wheelsets are connected to the bogie frame via the primary suspension. In car 1, 5 and 7, the machines and gearboxes are modelled as rigid bodies that are mounted on the frame. The railcar bodies are connected to the bogie via the secondary suspension, and they are connected to one another using joints and force elements. Between the railcar body pairs 1–2, 3–4, 5–6 and 6–7, there are joints that allow rotations about the vertical axis. The force elements there represent yaw dampers. The joints between the other railcar body pairs allow rotations about the transverse axis. This model serves as the baseline further changes are compared with.

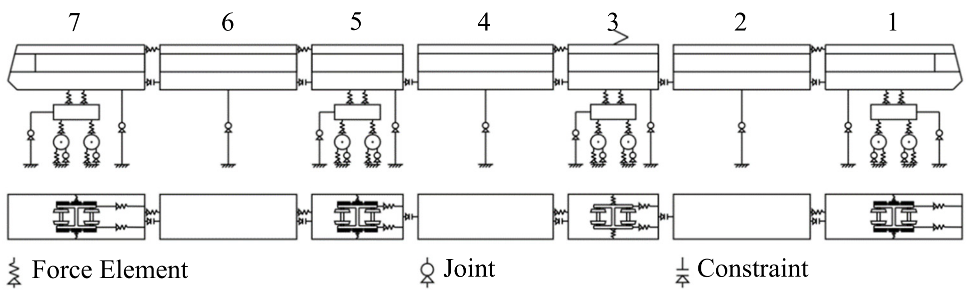

Figure 2: Topology of the Simpack model of the Flexity Zurich.

The model is equipped with acceleration sensors according to the standard [11], see Fig. 3. An end module, an intermediate car and a drive-less car are chosen to represent each type of car used in the vehicle.

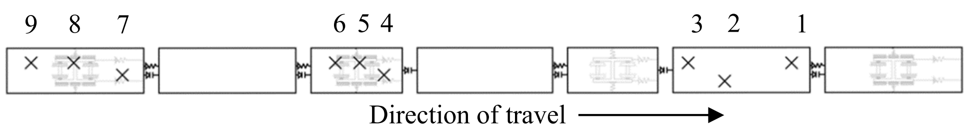

Figure 3: Placement of the acceleration sensors in the model, numbered from 1–9 starting at the head of the train.

The vehicle is placed on the track shown in Fig. 1 and pulled with the speed profile shown in Fig. 4. The speed profile corresponds to the real speeds at which the Flexity Zurich runs on line 9. However, the waiting times at the stops are shortened from 20 s to 10 s to save simulation time.

3.2.2 Concepts with high-speed machines

Two concepts with high-speed machines in the powertrain are simulated. This is achieved by changing the masses of the baseline vehicle according to Table 3.

There are two machines and two gearboxes per powered bogie. All bogies except the second one from the direction of travel are powered, see Fig. 3. In the baseline, the bogie

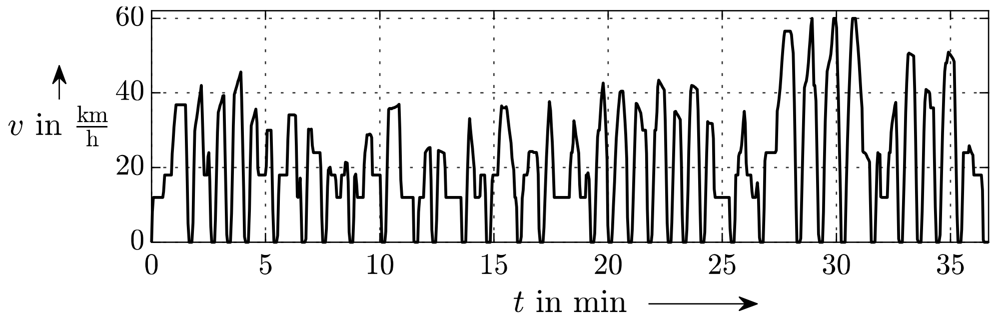

Figure 4: Speed profile of the Flexity Zurich on line 9

Table 3: Masses of the parts of the powertrain and the total masses from the baseline and two concepts.

Part	Baseline	Concept 1	Concept 2
Machine	336 kg (p)	125 kg (p)	125 kg (p)
Gearbox	285 kg (p)	310 kg (p)	310 kg (u)
Total mass (u)	1640 kg	1640 kg	2260 kg
Total mass (p)	2857 kg	2485 kg	1865 kg

Note: u = unsprung, p = primary suspended.

frame carries the machines and gearboxes, what makes them part of the primary suspended masses.

In concept 1, the conventional machines are replaced by high-speed machines which are significantly lighter than those of the baseline. However, the gearboxes require one stage more due to the higher revolution speed of the machines. Therefore, they are heavier than those of the baseline.

Concept 2 uses the same parts as concept 1. The difference, however, is that the gearboxes are attached to the swingarm of the wheelsets and not to the bogie frame. Hence, the gearbox masses are unsprung in this concept.

For concept 1, the primary suspended mass decreases by 13% per powered bogie. For concept 2, the changes lead to a reduction of the primary suspended by 35%. However, the unsprung mass increases by 38% in this concept.

3.2.3 Variation of unsprung und primary suspended masses

To determine the influence of unsprung and primary suspended masses on passenger comfort, two series of simulations are carried out. In the first simulation series, all unsprung masses are varied within a range of ± 40% in 10% steps. In the second simulation series, the same is done with the primary suspended masses.

4 RESULTS

This section presents the results of the simulations from Section 3. First, it shows the results of the baseline model, as these serve as a benchmark for its variations. Second, it presents the results of the two concepts. Finally, it shows the results of the simulation series in which the unsprung and primary suspended masses vary.

4.1 Baseline

Fig. 5 shows the ride index Wz both in lateral and vertical direction. The dashed line and the number above indicate the 95th percentile. In lateral direction, Wz according to sensor 1 was chosen and in vertical direction sensor 9, as these sensors detect the highest level of the ride index.

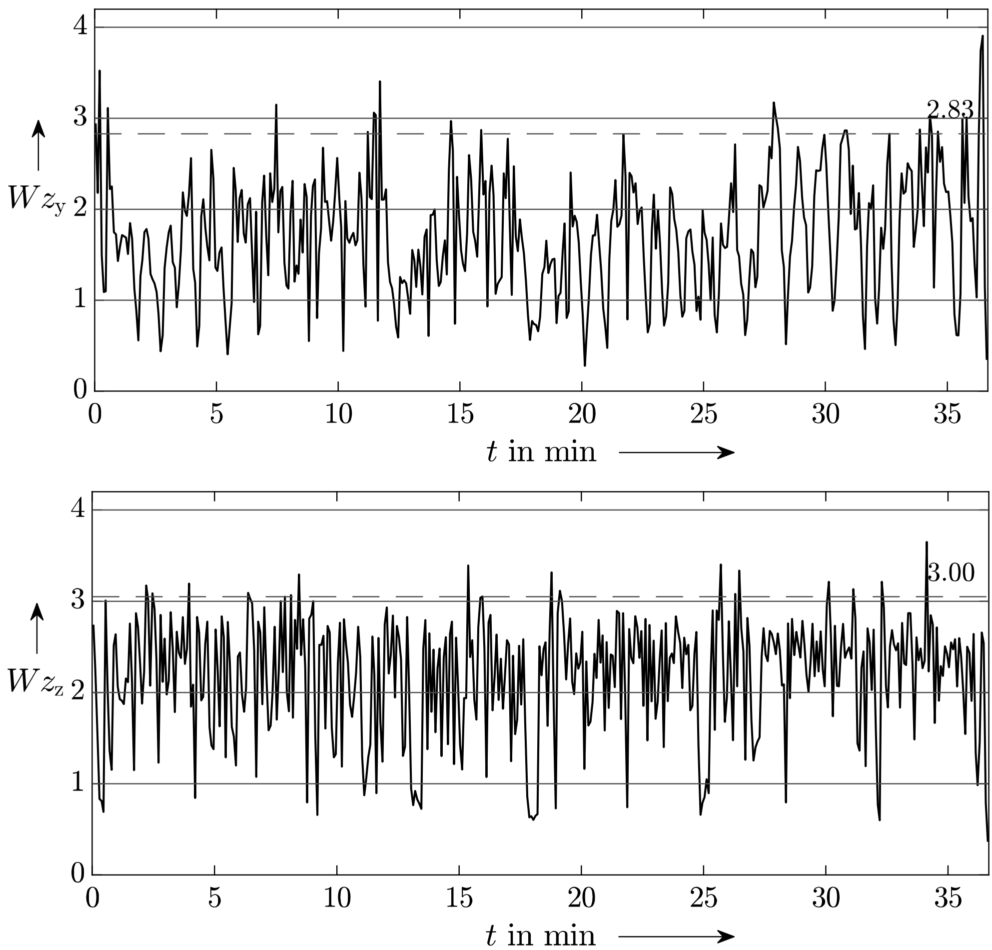

Figure 5: Course of ride index Wz of the baseline.

Most values are below 3.0 which corresponds to *Strong, irregular, but still tolerable* or better, see Table 1. Peak values higher than 3.5, which corresponds to *Extremely irregular, unpleasant, annoying; prolonged exposure intolerable,* are reached in lateral direction towards the end of the run. At this point, the vehicle travels through a turnaround loop. In vertical direction, this is the case on a hilltop the vehicle travels over.

Fig. 6 shows the course of the Continuous Comfort according to the same sensors.

Most values are below 0.2 and fall into the category *Very comfortable*, see Table 2. Peak values on this scale correspond to the same track events as on the Sperling scale in Fig. 5.

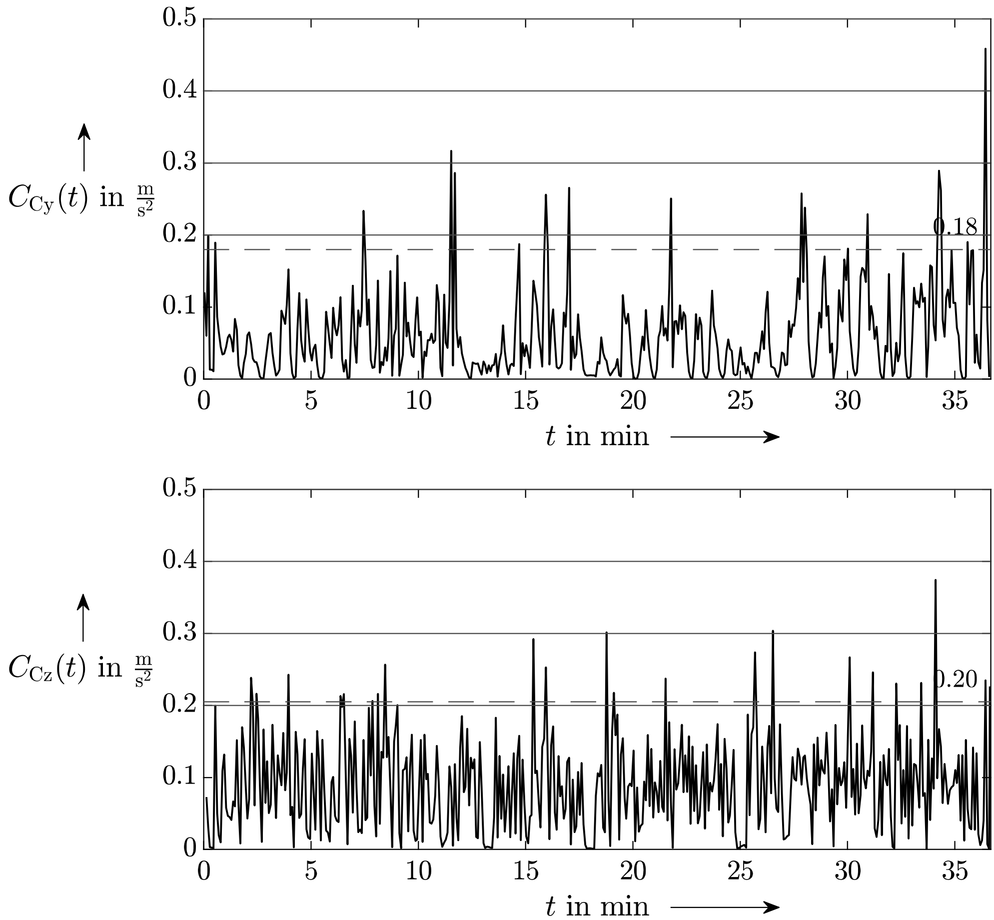

Figure 6: Course of Continuous Comfort C_{C} of the baseline.

4.2 Concepts with high-speed machines

To compare the concepts with the baseline with respect to the passenger comfort, the 95th percentiles of the comfort values of the sensors with the highest difference to the baseline are used. In lateral direction, this is the case for sensor 9 and in vertical direction for sensor 2. Table 4 gives the 95th percentiles both for the values on the Sperling scale and the scale of the Continuous Comfort.

Table 4: 95th percentiles of the ride index Wz and the Continuous Comfort C_{C} for the baseline and the concepts.

	Baseline		Concept 1		Concept 2	
	y	z	y	z	y	z
Wz	2.52	2.40	2.56	2.38	2.56	2.41
C_{C} in $\frac{\mathrm{m}}{\mathrm{s}^2}$	0.12	0.09	0.12	0.09	0.12	0.10

The biggest difference on the scale of the Continuous Comfort is 0.01 m/s^2 and on the Sperling scale 0.04. Therefore, the comfort values of the two concepts fall into the same categories as those of the baseline, so no noticeable changes are to be expected.

4.3 Variation of unsprung masses

In order to determine the passenger comfort as a function of the unsprung masses, the 95th percentiles of the ride index Wz are used. Sensor 1 reacts most sensitively to changes of the unsprung masses in the lateral direction, and sensor 4 in the vertical direction. Fig. 7 shows the ride index Wz as a function of the factor applied to the unsprung mass.

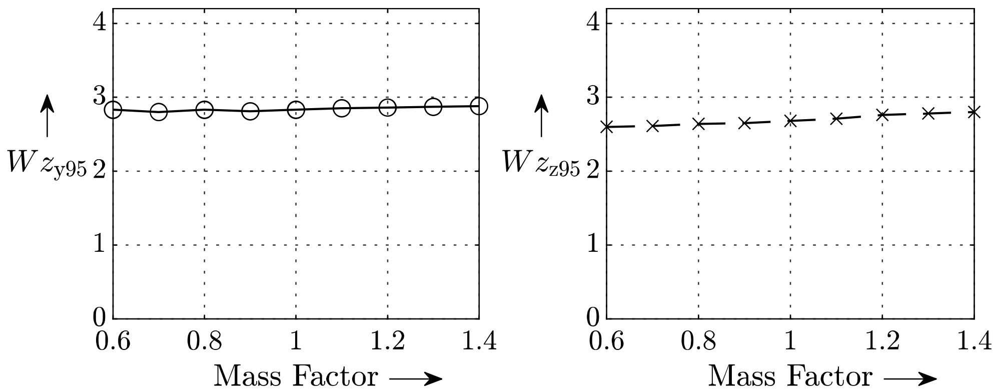

Figure 7: Course of Wz as a function of the unsprung mass in lateral and vertical direction.

In lateral direction, the values for Wz are in a range of 2.80 and 2.88, but no trend can be identified. In vertical direction, the values range between 2.60 and 2.80, and they fall steadily with decreasing unsprung mass. However, the extent is too low to cause perceivable changes in passenger comfort, as all the values remain in the same comfort category.

The scale of the Continuous Comfort turns out to be not suitable, as the changes are barely resolvable on this scale.

4.4 Variation of primary suspended masses

For determining the passenger comfort as a function of the primary suspended mass, the same procedure is used as in Section 4.3. Fig. 8 gives the ride index Wz as a function of the factor applied to the primary suspended mass.

In lateral direction, the values for Wz range between 2.84 and 2.87 with no discernible relationship to the primary suspended masses. Vertically, the values are between 2.62 and 2.85 with a trend towards better comfort values the lower the primary suspended mass becomes. However, like in Section 4.3, the differences of Wz are too low to cause perceivable changes in passenger comfort.

As for the unsprung masses, the scale of the Continuous Comfort turns out to be not suitable, as the changes are barely resolvable on this scale.

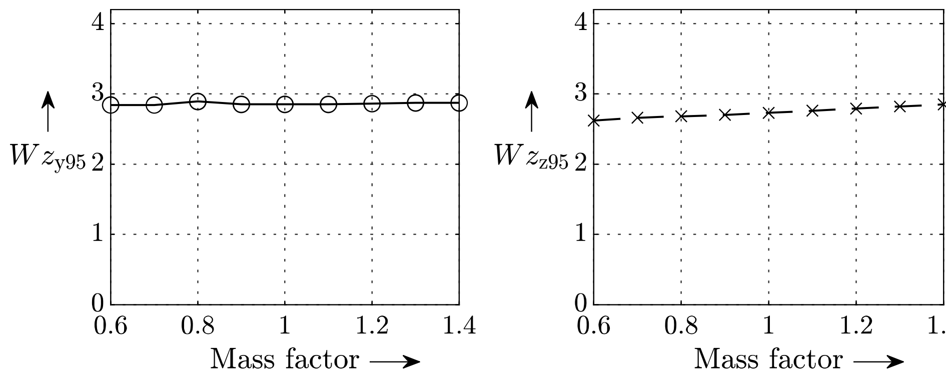

Figure 8: Course of Wz as a function of the primary suspended mass in lateral and vertical direction.

5 VALIDATION

To adequately validate the results, a field trial would be necessary. This is not possible within the scope of this paper, but the plausibility of the baseline model can be checked using literature values.

In Haladin et al. [7], acceleration measurements were carried out in two trams in the Croatian cities Osijek and Zagreb and evaluated according to the Sperling method and the Continuous Comfort method, as in this paper. With a length of 12.5 km, slopes up to 60‰ and velocities up to 50 $\mathrm{km/h}$, the conditions of the section in Zagreb are most comparable to those of this paper and are used to evaluate the plausibility of the results of the baseline model.

In Table 5, the distribution of the measured comfort values from the TKM2200, the vehicle in Zagreb, and the distribution of the simulated comfort values from the Flexity Zurich is shown on both the Sperling scale and the Continuous Comfort scale.

Table 5: Distribution of the measured comfort values from the TKM2200 in comparison to the simulated comfort values of the Flexity Zurich, percentage values.

	TMK2200		Flexity Zurich			TMK2200		Flexity Zurich	
Wz	Wz_y	Wz_z	Wz_y	Wz_z	C_C in $\frac{m}{s^2}$	C_{Cy}	C_{Cz}	C_{Cy}	C_{Cz}
<1.0	0.1	0.1	15.9	7.2	<0.2	97.8	86.4	97.3	94.5
1.0–2.0	33.9	35.6	51.6	26.6	0.2–0.3	2.2	13.6	2.3	4.8
2.0–3.0	65.9	64.2	29.8	60.7	0.3–0.4	0.0	0.0	0.2	0.7
3.0–3.25	0.0	0.0	1.8	4.1	>0.4	0.0	0.0	0.2	0.0
3.25–3.5	0.0	0.0	0.2	1.1					
3.5–4.0	0.0	0.0	0.7	0.2					

The majority of both the measured values and the simulated values fall into similar comfort categories. The values of the Flexity Zurich tend to a shift towards better comfort values. This is to be expected as it is a more modern vehicle. However, the model tends to rare but high peaks of bad comfort. This is considered unrealistic as bad comfort values do not occur at all in the vehicle in Zagreb. This can be due to uncertainties in the track model.

From the given track data, there were no information about transition curves and superelevations. These had to be assumed according to the official planning guideline in Verkehrsbetriebe Zürich [12], which does not necessarily represent real conditions.

6 CONCLUSION

This paper investigated the influence of modified powertrain masses on the ride comfort of a light rail vehicle. A multi-body model of Flexity Zurich, a tram operating in Zurich, was created using the software Simpack. The model was exposed to a run on the tramline 9 and evaluated according to common methods for determining ride comfort. These are the Sperling method and the Continuous Comfort method according to EN 12299.

The baseline model, which serves as a benchmark, reaches comfort values of which 95% fall into the category *Strong, irregular, but still tolerable* and better on the Sperling scale. On the Continuous Comfort scale, 95% of all values fall into the highest category, *Very comfortable*.

The concepts did not cause relevant changes in ride comfort in comparison to the baseline. This was the case although concept 1 leads to a reduction in primary suspended mass of 13% per powered bogie and concept 2 of 35%, but a 38% increase in unsprung mass per powered bogie.

In order to examine the effects of unsprung and primary suspended masses on the ride comfort, two simulation series were carried out in which both the unsprung masses and primary suspended masses were varied in a range of ± 40%. Even in this range, there is no relevant influence on ride comfort in lateral direction. However, a slight trend towards better comfort values with lower masses in vertical direction could be detected. But this influence is too small to cause perceivable changes in comfort, as all comfort values remain in the same category.

The model could not yet be validated, but in comparison with values from literature, it could be shown that it provides plausible results. However, the model tends to rare but high peaks which can be considered unrealistic.

To increase comfort, track irregularities and the suspension are probably of greater importance. Those factors were investigated in Dumitriu and Gheti [14] and correlated with the ride index Wz.

For validation purposes, measurements of the real vehicle could be taken and compared with the results of the baseline to evaluate the model.

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