Experimental testing of longitudinal acceleration in urban buses

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Abstract. A vehicle’s longitudinal acceleration is one the parameters that characterize a vehicle’s motion dynamics and used, among others, to assess the comfort of public bus passengers. Rapid acceleration and braking performed by urban bus drivers can be deemed by passengers as uncomfortable and dangerous in some situations, especially for standing passengers. This paper presents an analysis of a public bus’s longitudinal acceleration recorded during extreme acceleration and braking attempts. The experimental tests were conducted on dry and wet asphalt and concrete surfaces. The test results allow for the statement that lateral acceleration depends largely on the road’s surface and its type. The maximum longitudinal acceleration values during rapid acceleration, depending on the surface, are within the narrow range of 2.18–2.81 m/s². During braking, a public bus’s minimum longitudinal acceleration was within the range of -5.58–-8.54 m/s².

Keywords – lateral acceleration, vehicle, vehicle dynamics

1. Introduction
Vehicle experimental testing features bench testing and road testing. Due to the nature of the test subject, such testing includes the testing of specific elements, assemblies or complete vehicles. Complete vehicles are tested in road conditions [1,2], whereas specific elements or entire assemblies are tested on test benches [3-5]; however, there are test benches intended for conducting complete tests [6]. The manner in which tests are conducted depends mainly on the tests’ objectives. Road testing is intended to test specific vehicle assemblies [7-9].

A complete vehicle’s experimental testing can be conducted in terms of safety, technical properties, performance or dynamic properties. Depending on the conditions, vehicle testing can be conducted on public roads (in real traffic conditions), on isolated road sections that enable road testing in specific and repeatable conditions, e.g. on a test track or yard, and on various simulators (e.g. driving simulator, chassis dynamometer).

A vehicle’s dynamic properties depend on many factors. They can differ substantially depending on the operating conditions and manner of exploitation, the drive system type and the driver’s behaviour. One of the parameters that can be used to determine a car’s dynamic properties is longitudinal acceleration. This parameter is directly related to the vehicle’s longitudinal motion, i.e. with acceleration and braking performed by the driver. Longitudinal acceleration can be used to analyse and assess many aspects.
related to a vehicle’s correct operation and safety. It is also one of the parameters used in the dynamics and safety testing and analyses conducted for public buses.

A public bus is a vehicle designed to transport a large number of people over relatively short distances, characterized by frequent acceleration and braking. Aside from seats, public buses include space for standing passengers, wide and comfortable aisles between seats and wide entry doors. The dynamic properties of public buses differ substantially from the properties of passenger cars, commercial trucks and even long-distance buses.

The acceleration profile characteristics of public buses can be used to assess the drivers’ behaviour. In the case of public buses, the driver’s behaviour and driving style are important as they directly affect the passengers’ safety. The results presented in papers [10-12] confirmed that each driver views the environment in a unique way and reacts subjectively to the changing traffic conditions. Longitudinal acceleration exceeding 2.0 m/s$^2$ is deemed by passengers as very uncomfortable [13]. Papers [14,15] present longitudinal acceleration recorded at various speeds and in various traffic conditions, deemed as uncomfortable by sitting, standing and moving passengers. As demonstrated in papers [15-17], longitudinal acceleration exceeding 2.0 m/s$^2$ is dangerous for standing and moving passengers. Balance is at risk in possible-accident situations and the passengers may not be able to cling to the handrail. Some publications mention the limit value of 1.5 m/s$^2$, above which situations dangerous for standing passengers can take place in road traffic, e.g. on high-risk intersections [18]. The publication [19] demonstrates that this acceleration value is deemed as the equilibrium for a standing passenger that uses a handrail.

The use of adequate acceleration during possible accident reenactment can be an important aspect related to acceleration measurements during various manoeuvres [].

The purpose of this paper is to demonstrate the extreme longitudinal acceleration ranges for public buses recorded during rapid braking from 50 km/h and rapid acceleration from a standing start to 50 km/h. The experimental testing was conducted on specifically isolated test sections. The presented test results include longitudinal acceleration obtained on dry and wet asphalt and concrete surfaces.

2. Research methodology

The experimental testing included rapid acceleration and braking manoeuvres. The tests were conducted on test tracks with the following surfaces: dry and wet asphalt surfaces as well as dry and wet concrete surfaces. During the acceleration attempts, the driver was tasked with reaching the speed of 50 km/h from a standing start as soon as possible. During the braking attempts, the driver was tasked with stopping the vehicle from a starting speed of 50 km/h as soon as possible. For acceleration tests, the analyses considered the maximum acceleration value recorded during the road test. For braking, the minimum acceleration value recorded during the road test was considered for further analysis. Then, the maximum and minimum acceleration values recorded during the road tests were further analyzed.

The test vehicle was a public bus measuring 12 m in length, 2.42 m in width and 3.27 m in height. The vehicle’s permissible gross weight amounted to 18,000 kg. During testing, the bus was occupied by the driver and a person operating the measurement instrumentation. The measurement system installed in the vehicle featured the following:

- Corrsys Datron S-350® Aqua optoelectronic sensor;
- TAA® three-axis accelerometer;
- Datron uEEP12® data acquisition station along with a control tablet and the ARMS® software.

The following variables were recorded during the measurements: time, instantaneous speed, instantaneous acceleration. The recording frequency amounted to 100Hz. The effects of mass and tires on longitudinal acceleration values were not studied.

3. Results

The longitudinal acceleration values collected during the rapid acceleration and braking attempts were subject to statistical analysis. Figure 1 presents the distribution of the longitudinal acceleration values recorded for a public bus during braking attempts on an asphalt surface.
The negative longitudinal acceleration obtained during braking attempts was in the range of -8.54÷-7.96 m/s$^2$. The average acceleration recorded during the braking attempts amounted to -7.96 m/s$^2$, whereas the standard deviation amounted to 0.27 m/s$^2$. The average negative acceleration recorded for the public bus on a wet asphalt surface was approx. 8% lower than that recorded on a dry surface and amounted to -7.35 m/s$^2$. The acceleration’s standard deviation during the braking attempts amounted to 0.32 m/s$^2$. The acceleration recorded during the braking attempts on a wet asphalt surface was in the range of 2.89÷4.42 m/s$^2$. The standard deviation of acceleration obtained during braking attempts performed for various surfaces was small and amounted to 0.27 m/s$^2$ and 0.32 m/s$^2$, respectively, thereby pointing to a high concentration of the obtained results and the measurements’ correctness.

Figure 1. Distribution of minimum longitudinal acceleration during braking attempts on an asphalt surface.

Figure 2 presents the distribution of acceleration values recorded during braking attempts on a concrete surface.

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Figure 2. Maximum lateral acceleration values recorded when driving on a circular asphalt track.
During the public bus’s braking attempts on a dry concrete surface, the delay was in the range of \(-7.58\div-7.01\) m/s\(^2\) and the designated average negative acceleration amounted to \(-7.01\) m/s\(^2\), whereas the delay’s standard deviation amounted to 0.49 m/s\(^2\). On a wet concrete surface, the average negative acceleration was smaller by over 26% when compared to the dry surface and amounted to \(-5.15\) m/s\(^2\) with a standard deviation of 0.26 m/s\(^2\). In this case, the acceleration recorded during the braking attempts was in the range of \(-5.58\div-5.15\) m/s\(^2\).

Figure 3 presents the distribution of the minimum longitudinal acceleration values recorded for a public bus during braking attempts on an asphalt and a concrete surface.

![Figure 3](image)

**Figure 3.** Minimum longitudinal acceleration recorded during braking attempts

The lower of the longitudinal acceleration values (\(-8.54\) m/s\(^2\)) during rapid braking attempts was recorded on a dry asphalt surface. On a wet asphalt surface, this value was 8% higher than the minimum acceleration recorded on the dry asphalt surface. Higher longitudinal acceleration values were recorded during braking attempts on a concrete surface. The lowest acceleration was recorded during braking on a wet surface and amounted to 5.58 m/s\(^2\).

The acceleration intensity is a relatively important parameter that can be taken into account when dealing with the comfort and safety of public buses. This parameter determines the possibility of dangerous situations occurring during passenger transport, but also affects the driver’s ability to perform defensive manoeuvres (rapid acceleration) in road traffic [20-23]. Figure 4 presents the distribution of longitudinal acceleration values recorded for a public bus during acceleration attempts on an asphalt surface.
During attempts to rapidly accelerate with a public bus from 0 km/h to 50 km/h on a dry asphalt surface, the acceleration was in the range of 1.92÷2.18 m/s². The average acceleration during the attempts performed on a dry asphalt surface amounted to 2.03 m/s², whereas the standard deviation amounted to 0.08 m/s². The acceleration recorded on a dry asphalt surface was slightly higher and was in the range of 1.52÷2.33 m/s². The acceleration’s standard deviation during the attempts amounted to 0.81 m/s². The average acceleration on a wet asphalt surface was lower by 5.9% than the value obtained on a dry surface and amounted to 1.91 m/s². Figure 5 presents the distribution of longitudinal acceleration values recorded for a public bus during acceleration attempts on a concrete surface.
The public bus’s acceleration values recorded during rapid acceleration on a dry concrete surface were higher than the ones presented earlier and were in the range of 2.51÷2.81 m/s². The average acceleration during the attempts performed on a dry concrete surface amounted to 2.64 m/s², whereas the standard deviation amounted to 0.10 m/s². The acceleration recorded on a wet concrete surface was in the range of 2.21÷2.55 m/s². The acceleration’s standard deviation during the attempts performed on a wet concrete surface amounted to 0.09 m/s². The average acceleration was lower by 7.9% when compared to the dry surface and amounted to 2.43 m/s².

Figure 6 presents the maximum acceleration values recorded for a public bus during rapid acceleration on the various surfaces aforementioned.

![Figure 6. Maximum acceleration values recorded during acceleration attempts](image)

The highest acceleration values obtained during rapid acceleration were recorded on a concrete surface. The highest acceleration here was recorded on a dry surface and amounted to 2.81 m/s². The maximum acceleration value recorded during the attempts on a wet concrete surface was lower by 9% than the maximum acceleration value recorded on a dry concrete surface. The lowest acceleration values obtained during the acceleration attempts were recorded on a wet asphalt surface. The highest acceleration recorded during the acceleration attempts on a wet asphalt surface amounted to 2.33 m/s².

4. Conclusion
In order to obtain reliable and real longitudinal acceleration values, it is necessary to conduct adequate tests using dedicated instrumentation. The longitudinal acceleration values obtained in the experimental testing provide reliable information about a vehicle’s dynamic properties. In the case of public buses, the longitudinal acceleration values recorded during braking and acceleration are an important parameter that determines the passengers’ comfort and the ability to perform effective defensive manoeuvres. The results of the performed rapid acceleration attempts demonstrated that the acceleration values depend on the surface’s type and condition.

Depending on the surface type, the maximum longitudinal acceleration values recorded during rapid acceleration are in the range of 2.18÷2.81 m/s², whereas during rapid braking – 5.58÷8.54 m/s². The obtained acceleration values differing for various roads and measurement conditions demonstrate the need to conduct further related research. As is shown, the measured values are substantially affected by the surface type, and surface types are rather diverse. As demonstrated in the Report on the technical
condition of roads in 2020 in Poland [24], nearly 60% of roads are in good technical conditions but nearly 14% of roads are in a bad condition. This is related to the substantial differences in the friction coefficient between the best and worst road sections, which broadens the perspective for further research.

As can be seen from the presented road research, the type and condition of surface has a significant impact on the values of longitudinal accelerations. Therefore, it is worth to extend the research with the analysis of the influence of vehicle load and different types of tires.

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