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Simulation of operating loads of a city bus powertrain

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Abstract. The paper presents a method to simulate operating loads of a city bus powertrain performed to get an estimation of percentage shares of load distribution (driveshaft torque values) for a city operation of a bus. The method assumes connecting the operating tests with a computer simulation which combines a signals of powertrain loads from samples recorded in a various operating conditions (the weight of the bus/number of passengers, road slope, average speed for short distances) due to different traffic characteristics changing with topography and the time of the day. The sources and ways to collect information about these variables are presented. The next part of the article presents an operating road test and method of measurement drive shaft torque. Also alternative method of estimating drive shaft torque signal with use of the recorded bus velocity signal and a topography information with bus passenger load factor information was presented. The simulation procedure which was presented and statistically processed results in the form of a 2D histogram of frequency of occurrence of particular torque values. The final part of the paper presents a result of a comparison of percentage share of particular torque variability for all-day operation for a chosen route in Warsaw obtained during proposed simulation with a similar percentage share obtained for loads registered within independent road test on the same route..

1. Introduction

City busses are a characteristic type of vehicles. They are used in special operating conditions, very difficult for a powertrain system, but repeatable. These conditions result from urban traffic characteristics and bus routes characteristics. These conditions can be defined as a series of data points representing speed versus time and are called a driving cycle. They can also be represented by speed and gear selection as a function of time and speed versus distance or time versus road slope.

Specific features of city bus driving cycles are low average speeds, high number of acceleration and deceleration phases due to pulling away from stops, pulling over at stops and driving in congested traffic in stop-and-go conditions with usually short segments of driving with constant speed.

Modern city buses also have a very specific design of a powertrain system, resulting from demands and expectations of low-floor body. This powertrain system has a specific configuration of a drive shaft resulting from a use of special low-floor portal driving axles and tower-design engine non symmetrically mounted in a bus. Therefore in a case of three axle buses the configuration of a drive shaft is non symmetrical in a horizontal and vertical planes and special configuration of drive shaft needs to be used – in a horizontal plane Z configuration is used and in a vertical W configuration is used [6]. An example of that drive shaft assembly is presented in figure 1.

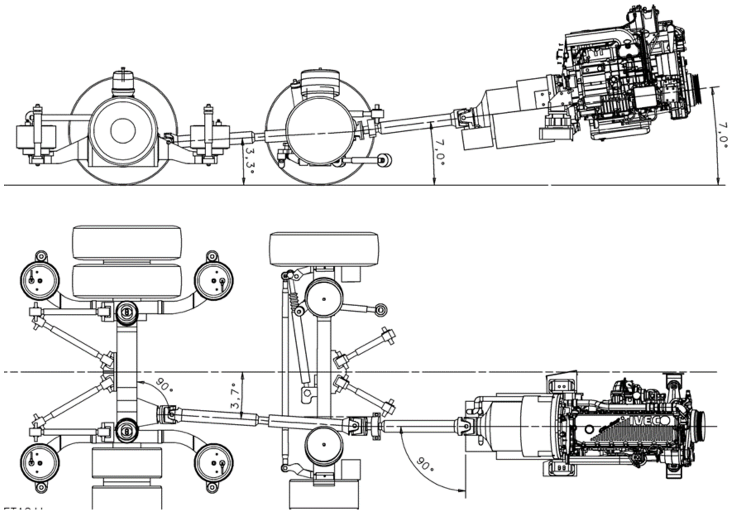

Figure 1. The drive shaft assembly of 15 m long low floor city bus

Such an assembly configuration may cause dynamic loads in drive mechanism due to a problem with obtaining the full compensation of working angles for the whole drive shaft. It may cause problem with durability of bus drivetrain elements because of producing drivetrain torque sinusoidal changes around the average value equal to the torque at the drive shaft input. It will also produce vibration and noises in the drivetrain system.

The amplitude of torque fluctuations depends on the working angle inequality and the value of input torque, which is affected by demand of tractive torque on the driven axle. The values of tractive torque depend on the driving cycle typical for chosen operating conditions. While designing it is useful to know the level of demanded torque or the spectrum of this torque if it is highly variable.

In this paper the idea of simulation of a city bus powertrain operating loads – mainly the percentage share of particular torque values – was proposed.

2. Idea of the operating loads of a city bus powertrain simulation with use of real test data

The idea of the operating loads of a city bus powertrain simulation assumes that it is possible to build a long period estimation of operating load signals connecting together segments of torque versus time and velocity versus time signals from road tests made for specific conditions of the bus operation. The sequence of subsequent segments is driven by the specially designed matrix of operating conditions corresponding to discretized changes of operating conditions observed in real life.

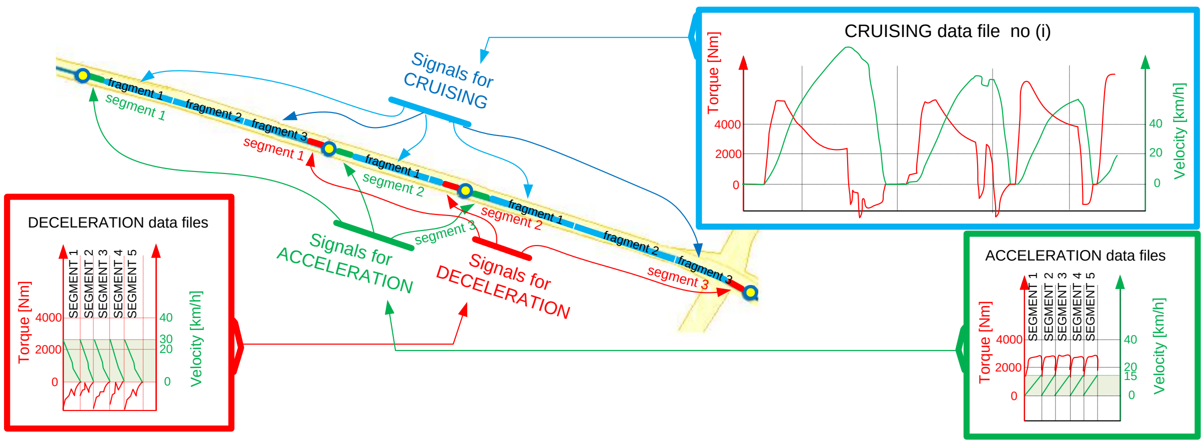

Figure 2. The idea of operating load simulation with use of real life data

The main features of this idea are:
- possibility to transfer information about real life operating loads for the same vehicle one city to another on the basis of real data collected in one place and information about operating conditions in another place,
- possibility to get stochastic result of the simulation using a set of files recorded for the same discretized operating conditions and using a randomly selected file while connecting signals for the next segments,
- possibility to take into consideration a specific design of the vehicle due to use of real life torque signals,
- speeding the process of obtaining estimated operating loads and achieving economic benefits due to shortening or skipping unnecessary road tests in a new operation place.

3. Input data for simulation

There are three groups of data used for simulation:
1. the route information – distances of subsequential bus stops from the bus depot and subsequential times of departures from these stops, topographic information about route localisation and road elevation,
2. matrix of operation conditions composed to describe discrete changes in operation conditions and bus parameters,
3. real life test data (driveshaft torque and angular velocity signals) from the bus operation at various condition.

3.1. The route information

The route information about distances of subsequential bus stops from the bus depot and subsequential times of departures from these stops controls the process of simulation. The real operation data segments are connected to fill the whole distance defined by the route information. An example of the file defining the route distances and the chart illustrating bus stop distances along the whole route is presented in figure 3.

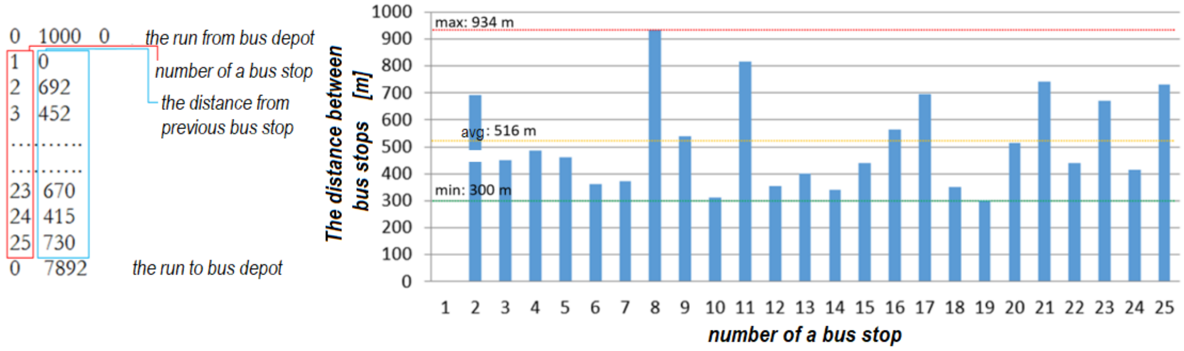

Figure 3. The structure of file defining distances between stops and chart showing their values for tested bus route

3.2. Matrix of operating conditions

During the estimation of operating loads signals for short segments are connected. The decision about selecting file corresponding to actual operating condition is made on the base of operating condition matrix and the time elapsed and distance traveled by bus during the simulation.

The operating condition matrix was designed after deciding which parameters of a vehicle and the route affects torque values and determines variability of a powertrain loads. After an analysis the authors defined them as follows:

1. vehicle parameters:
   - number of passengers affecting city buss actual mass,

2. route parameters:
    - number of stops and distances between them,
    - average speeds on route sections between the stops,
    - geographical location of bus stops,
    - the road slope between the stops.

These parameters were discretized for :

- time of day – the single step was 1 hour,
- place of operation – the discretization step was one segment between bus stops,
- parameters values defining conditions of operation:
    - road slope – 2 ranges were used,
    - segment average speed – 4 ranges were used,
    - number (mass) of passengers – 2 ranges were used.

The discretization speeds up the simulation, but affects the result accuracy. However, it is important to remember that it is also difficult to define them in practice for very short time periods or distance step and also with a big resolution of parameters, as this would make the proposed method useless because of workload and time consumption. Selecting representative operation conditions needs some expert knowledge and for the sake of the example this was bus driver's knowledge. But it can also be a topic of dedicated tests and analyses.

Due to discretization of operation condition parameters limited number of files were collected. For the changes of bus mass, two load cases were assumed – 50 and 100% of passenger capacity – and special masses were used to simulate an adequate mass of passengers.

The information what is **actual passenger capacity utilization rate** (or passenger load factor) can be collected manually or automatically. Manual collection is time consuming and subject to inaccuracy but sometimes it is the only way to obtain such data. Nowadays many automatic passenger counting (APC) systems are available – infrared (IR) based systems – beams and optic, low ultrasonic frequency sensors, stereo-vision based systems, treadle mats, turnstiles and load cells with pneumatic pressure sensors used to detect the load on the bus suspension [5]. It is also possible to use the information from electronic ticket systems.

The information about route **topography** (geographical bus stop location and road elevation) can be now obtained from GIS (geographic information systems), for example from free-to-use and easily accessible mapping software such as the proprietary web applications Google Maps and Bing Maps, as well as the free and open-source OpenStreet Map.

For the route used for exemplification of the method, on the basis of data gathered from web software GPSVisualizer [2] – figure 4, two ranges of the road slope were selected for use after discretization – 0…1 % and 6…8%.

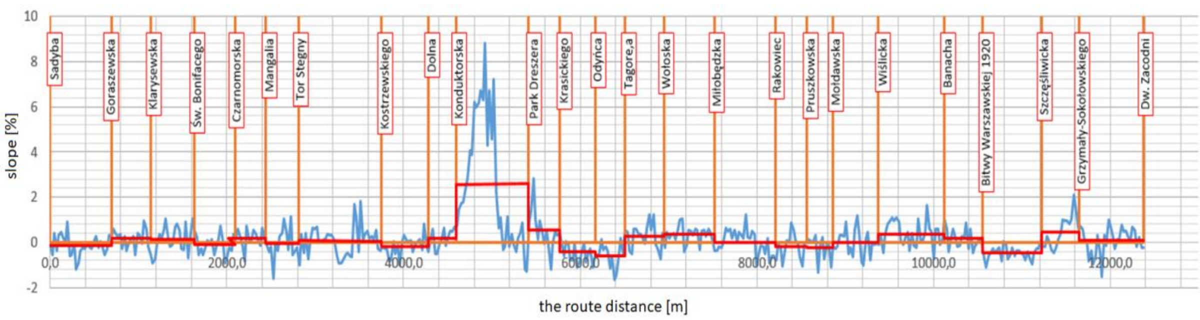

Figure 4. The slope for 172 Warsaw bus route

Data about **average speed over route segments** can be obtained from on-board velocity recordings and also from GIS web software with traffic information layers. The first source of information, based on GPS receiver become popular last years and a lot of tracking devices now are available with sampling frequency from 1 to 10 Hz – for example specialized for automotive measurements Reclogic products or general purpose devices for example from Garmin. The GPS tracks are useful when there is a possibility to record such information operating already owned bus fleet on the same routes. Then it can be the most reliable source of information.

If there is no possibility to record such information, the information recorded automatically from the other users using location services can be used, for example from Android smartphones, or on-line navigation systems like Naviexpert. That method of gathering data about traffic characteristics is known as FCD - Floating Car Data, FTD Flotaing Truck Data, Floating Bus Data [7]. Using specially designed web services of these locations or navigation services operators, like for example the journey planner of NaviExpert with technology „Community Traffic online" [1] the predictive information about changes in average speed can be obtained along the selected roads during the subsequent hours. This information is based on the collected an assortment of data concerning the current traffic situation, which are stored, processed and finally used to recommend the best routes during the navigation phase. Average times of traveling on route segments were determined using journey planer for traffic changing conditions with one hour steep. The variations of the route run times estimation determined with use of the journey planner are presented in the figure 5.

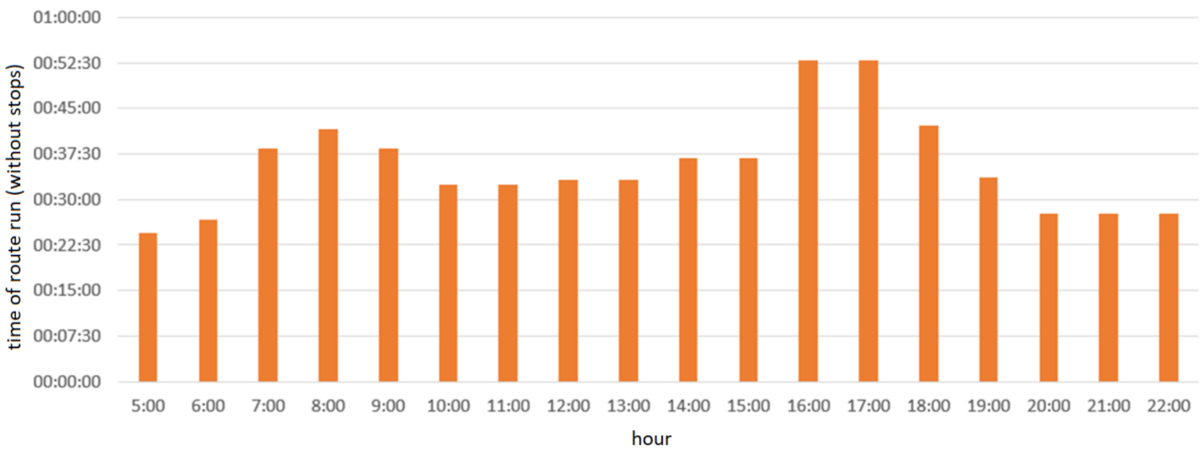

Figure 5. Different duration times of Warsaw 172 route run during the day

On the base of assumed discretization of operation time (1 hour) and discretization of route length (one segment was equal to the distance between two successive stops) and also the data about travel time obtained for segments it was possible to design and fill matrix of operating conditions. The matrix columns represents route successive segments and rows successive hours of city bus operation. Elements of matrix are coded with 3-digit code describing:

- average traffic (bus) velocity on the segment,
- passenger load factor (the passenger capacity usage ratio),
- average road slope for segment.

The operating conditions matrix governs real operation load data selection during realization of the operating loads simulation procedure.

Figure 6. The operating condition matrix structure for tested bus route

3.3. Real operation load data

Data files with time histories of the city bus drive shaft torque and velocity are the source of information about operating loads of city bus drivetrain system. These data files were recorded during short periods necessary to record representative fragments of bus operation in representative conditions (bus load, type of traffic – average speed) and fragments of routes.

For the exemplification of the proposed method data files were recorded with use of two types of sensors:

- inline torque sensor prepared with use of strain gauges bonded to a typical drive shaft used in a city bus and a telemetric technology of measurement signal transfer,
- wheel angular speed sensors mounted on the left and the right wheel of driven axle.

Data files were recorded during runs along the selected representative segments of bus routes in different hours characterised by the various traffic conditions with two cases of simulation of passenger capacity utilization factor.

Data processing consisted of following steps:

- extracting bus run specific fragments:
  - acceleration from stop to 20 to 50 kph and situation when the driveshaft torque decreases below zero,
  - deceleration to stop,
  - cruise at variable speed between the acceleration and deceleration phases,
- naming and organising files in order according to operating conditions (bus passenger capacity utilization ratio, road slope) and average speed cruising between the stops, final speed of acceleration segments and beginning speed of deceleration phase.

The names for data files were composed from one of three possible names describing phases of bus operation – *acceleration*, *deceleration* and *cruising* and 4-digit code. The first 3 digits in the code are described in the previous paragraph - Figure 6. The last fourth digit is describing the next order number in a group of data corresponding to the same conditions of average traffic velocity on the segment, passenger load factor (the passenger capacity usage ratio) and average road slope for segment.

3.4. Backward facing simulation of drive shaft torques on the base of real operation velocity data

An alternative to on vehicle measurement of driveshaft torques there is a possibility to simulate torque values with use of backward-facing model (Fig. 7) which has the ability to calculate of the drivetrain torques to meet the demands of the drivecycle. Based on the speed trace recorded with GPS data logger, the resultant force at the tyre contact patch is calculated, where it is converted into wheel torque and propagated back to the engine via the drivetrain, along with angular velocity [3].

The road slope along the route was determined from topographic data on the base of registered GPS track with use of GPSVisualizer web software.

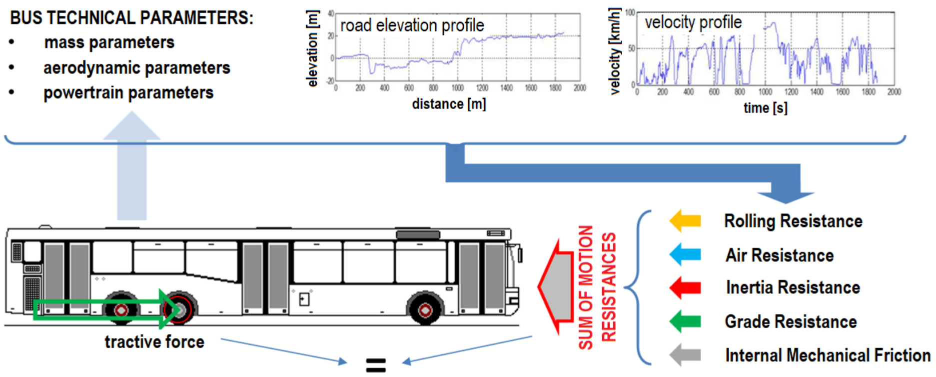

Figure 7. The idea of backward facing bus longitudinal dynamic simulation

A quite simple and obvious model of vehicle demand for tractive torque on a driveshaft had to be complemented with the following modules:

- module of interpolating driven distance to adequately interpolate road height and calculate road slope,
- module of calculating braking forces on a drive shaft due to retarder use in a city bus,
- module to limit the drive shaft braking torque when service brakes are in use.

The result of model verification, i.e. a comparison with real life test data is presented in figure 8.

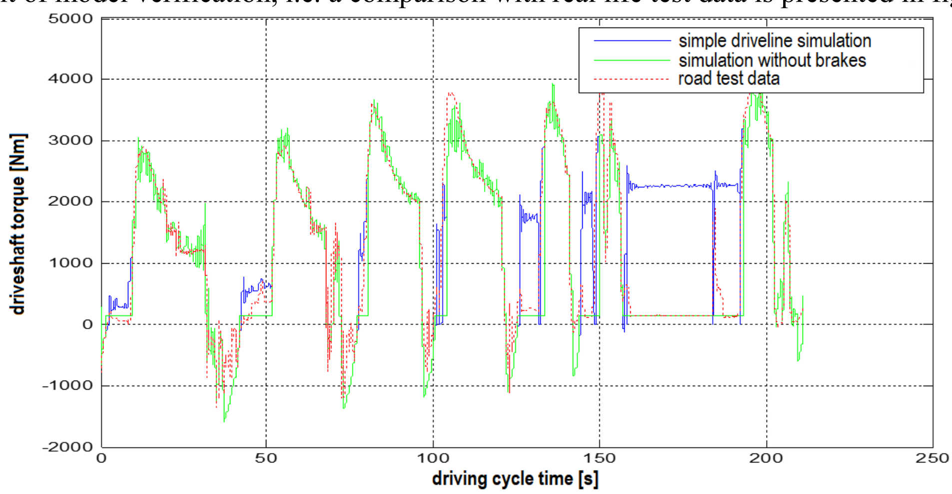

Figure 8. The simulated (simple simulation and simulation with compensation of brake torques) and real test drive shaft torques

The results show that this type of simulation allows to calculate demanded torques on the basis of the route data and velocity signal of the bus.

4. The operating loads simulation procedure

Developed city bus operating loads simulation procedure consist of the following main steps – figure 9:

1. loading input data:
   - route definition - information about subsequent bus stops and distances between them,
   - scheduled departures times from bus depot,

   - matrix of operation conditions,
2. simulation of operating loads (driveshaft torques and corresponding angular velocities) - selecting and connecting fragments of torque and velocity signals selected according to code read out from matrix of operation condition and calculation of travelled distance. This processes were done for:
   - simulation of bus run from bus depot to bus terminus (a designated place where a bus starts or ends its scheduled route),
   - simulation of bus runs along the route:
     i. definition of number of bus courses (runs) back and forth,
     ii. definition of scheduled times of departure from a bus terminus
     iii. simulation of bus runs along the route - for one segment is illustrated in figure 8,
   - simulation of a bus run from last bus terminus to bus depot.
3. An analysis of obtained torque and angular velocities of the city bus drive shaft for whole day operation - the percentage share of particular torque and velocities values calculation.

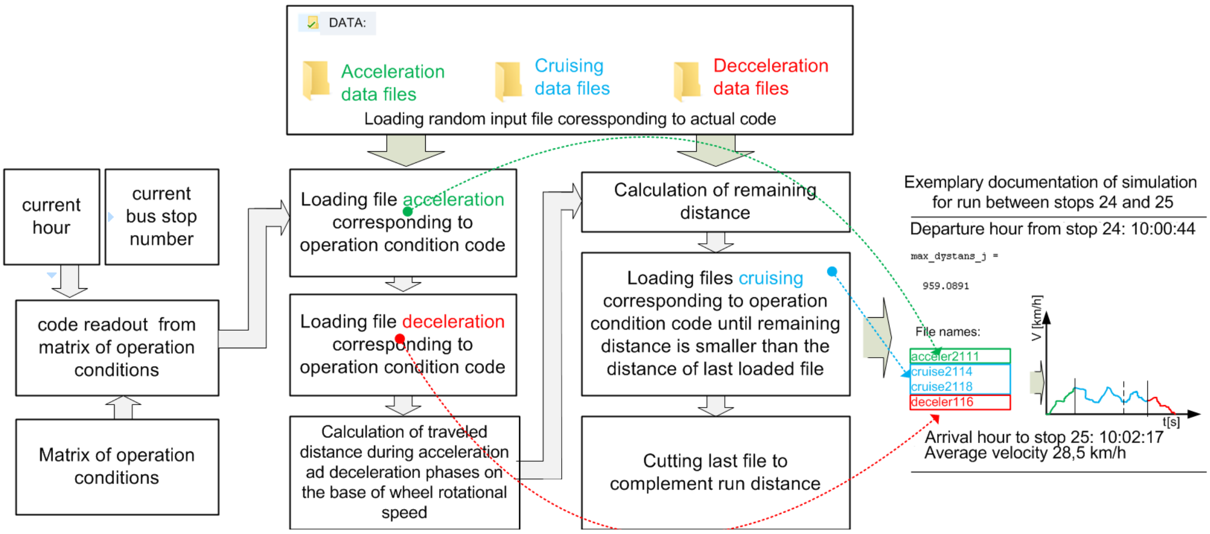

Figure 9. The procedure of simulation of torque and velocity signals for bus run between stops

The important step during simulation was to calculate the distance travelled at one simulation step and a cumulative distance, as it was one of the important data necessary to determine corresponding to actual bus location file code and to calculate remaining distance.

During the simulation of bus run between stops the whole process was simulated adding acceleration and deceleration phases distances and later adding cruising phases as long as the whole remain distance would be covered with combined files. The last file was truncated if necessary to fill the whole distance and to make it close to distance between stops.

5. The results

The simulation for the whole day and week of vehicle operation gave the results in a form of time history of torque and angular velocities of drive shaft. That form of results has low interpretation value, thus it was statistically processed. The two-dimensional histogram of relative frequency of particular value occurrence was calculated on the matrix of torque and angular velocities. The width of torque was 100 Nm and the width of angular velocity was 50 rpm. The calculated histogram is presented in figure 10 and shows that the most frequent are values around 0 Nm torques with the predominance of positive values.

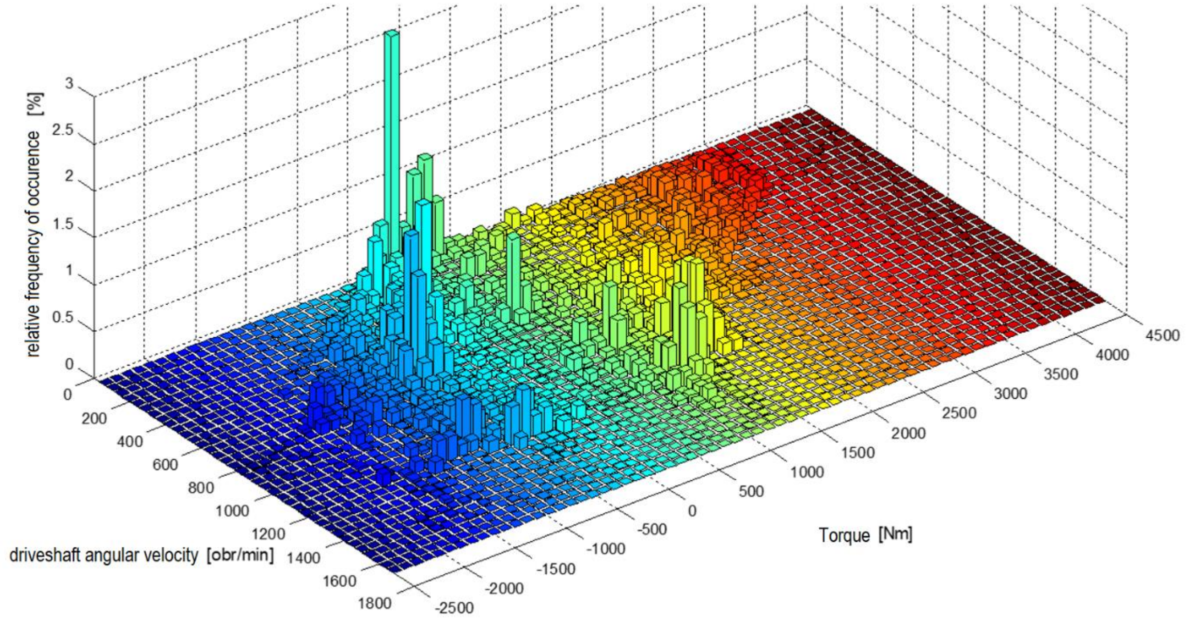

Figure 10. Two-dimension histograms of particular torque and angular velocities of the city bus driveshaft

To verify the proposed method of simulation of the operational loads of powertrain, estimated relative frequency of particular drive shaft torque value occurrences were compared with similar relative frequency occurrences obtained from real life operation tests. These one-week operation tests were performed by manufacturer of the powertrain on bus 172 route in Warsaw with specially instrumented driving axle. The result of this comparison is presented in figure 11.

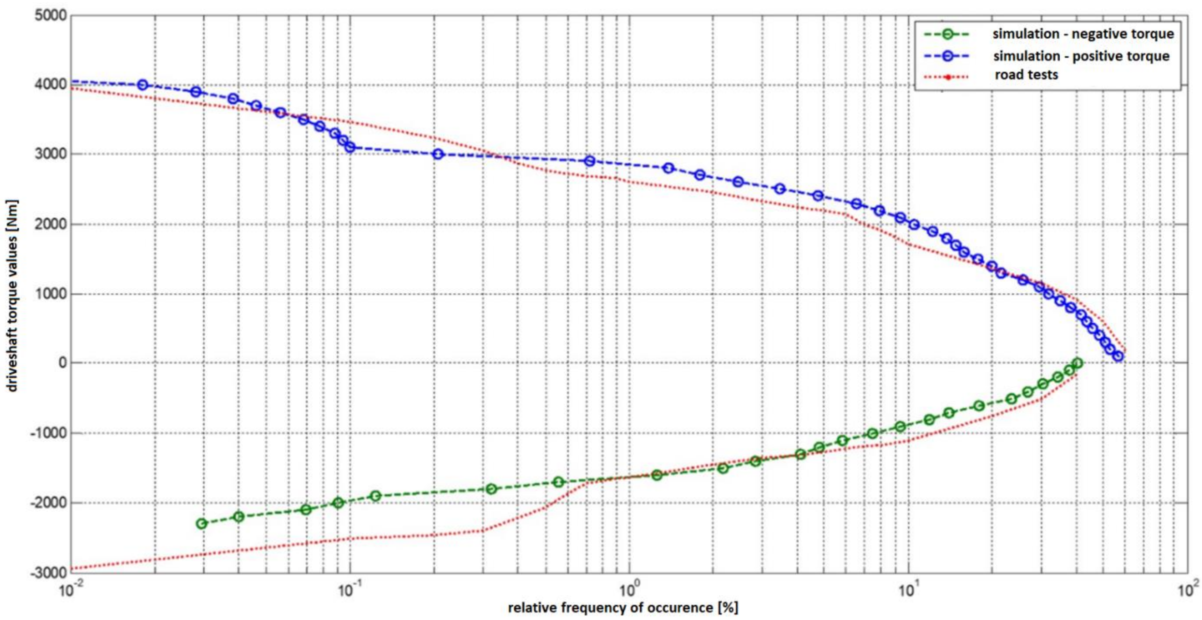

Figure 11. The comparison of relative frequency of occurrence of particular driveshaft torques occurrence for simulation and road test

An analysis of differences between test and simulation torque values for given relative frequency of particular drive shaft torque value occurrences showed the average 10% difference in relation to torque values obtained from tests. The biggest differences were for the smallest values of torque and at the same time highest relative frequency of occurrences – up to 40% of torque values form the test. Simulation values of torque were smaller. For the highest torque values differences were between 4 and 11% and simulated values were bigger.

6. Conclusions

The presented method of estimation operation loads of a city bus power train has an utilitarian value. It allows to estimate the percentage share of particular torque and particular angular velocities using two sources of real life signals for torque and angular velocities of drive shaft:

- road tests of torque and angular velocities of drive shaft,
- road test of velocity profiles of a city bus and simulation of time histories of torque and angular velocity signals.

The operating condition matrix allows a repeated use of signals recorded only for representative fragments of vehicle operation. The content of the matrix can be estimated on the base of information accessible from modern Intelligent Transportation Systems and sometimes allows to prepare such a matrix for new localization for bus operation on the base of data obtained from these systems.

The operating loads and results of their systematization with use of statistical analysis obtained as a result of simulation the torque values in the individual speed and torque ranges forms the spectrum of operational loads of a vehicle powertrain what allows to analyse the specificity of the operation of the city bus powertrain system on a specific routes. It allows also to use so obtained information during parametric identification of powertrain processes [4] and estimate durability of a powertrain components – for example fatigue life determination of drive shaft or bearings used in a powertrain components.

Backward facing simulation of drive shaft torques on a base of real operation velocity data allows to limit measurements in road test only to recording of bus speed profile, what can be done today with quite cheap and easy to operate GPS tracking devices.

The accuracy of obtained data is strictly dependent on quality of simulation input data, but there is also relation between data accuracy, resolution and cost. Proposed method could be used also for a coarse but fast and cheap estimation of operating loads but also with use of more accurate and dense input data for more accurate estimation of operating loads.

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