12th IMEKO TC10 Workshop on Technical Diagnostics
New Perspectives in Measurements, Tools and Techniques for Industrial Applications
June 6-7, 2013, Florence, Italy

Techniques for on-board vibrational passenger comfort monitoring in public transport

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***Abstract*-**Traffic calming devices on urban streets, such as elevated pedestrian crossings, speed bumps and roundabouts, are increasingly used, therefore bus passengers on-board comfort assessment is an actual problem.
In order to measure vibrational on-board comfort for public transport standing passengers related to traffic calming, an acquisition system called ASGCM (Autonomous System for Geo-referenced Comfort Measurements) has been developed, taking as a reference the European regulations on rail transports. Thanks to ASGCM, each measurement of vibration, on-ground velocity and acceleration is linked with geographical information resulting from a GPS, so a map of a comfort index, as well as statistical surveys and correlation between on-board comfort and traffic calming, can be directly obtained using a Geographic Information System (GIS), querying a centralized remote database developed ad-hoc. A large number of experimental tests has been performed in order to define a vibrational comfort index and to collect a large statistics that allows a significant comparison between different infrastructures and their characterization. The proposed technique can also be useful for diagnostics purposes, such as vehicles comparison and vehicle and road maintenance state monitoring.

I. Introduction

Developments in laws [1] and some researches [2, 3, 4] have put in evidence two different aspects that could seem to be opposed: one is the necessity to improve road safety, introducing traffic calming measures, such as roundabouts, speed bumps, chicanes, elevated pedestrian crossings or different type of pavements; the second is the attention to control workers and passengers vibration exposure on public transport vehicles and to improve transport quality. Until now many authors have been studying traffic calming devices and public transport passengers interaction [5, 6, 7, 8].

The purpose of this work is to give useful information to both vehicles and infrastructures designers; in particular this research is aimed to define a technique to evaluate how traffic calming devices affect road public transport passengers perceived accelerations and to provide a low cost device to easily measure and supervise vibration level on road public transport. Therefore, taking as a reference the European regulations on rail transports [9], the researchers propose the definition of a vibrational comfort index, which allows to characterize and compare different road infrastructures and that could also be useful in order to compare different vehicles behaviour related to road infrastructure and to monitor vehicle maintenance state.

II. Measurement and processing system

In order to supervise on-board comfort, two quantities are needed: comfort level and geographical location. The measurement chain, shown in Figure 1, consists of a capacity triaxial accelerometer mounted along the three principal orthogonal axes, of a NI Compact-RIO, of an analogue input module, of some supply and connection cables, of a commercial GPS antenna, and of an USB Flash memory. Both the accelerometer and the NI Compact-RIO are powered by a battery.

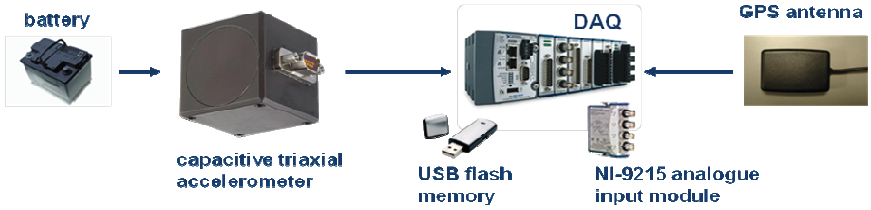


Figure 1. Measurement chain

Comfort level has been calculated taking into account both infrastructure effects, involving low frequencies, and vibration effects. These have been measured using a triaxial accelerometer, with an acquisition rate of 1000 Hz and a buffer of 1000 samples. In a second of acquisition the buffer is filled up and data are processed using a band-pass filter, from 0.5 Hz to 300 Hz, designed according to human response to vibration filters [9, 10]: Acceleration magnitude is computed as a vector sum of the three accelerations acquired in orthogonal directions (x axis corresponds to the road direction, y is in the road plane and orthogonal to x, z is perpendicular to the road plane) and an RMS acceleration value is calculated, considering a period of 5 seconds. This period of time represents a compromise between low frequency vibrations acquisition and a statistically relevant number of samples.
The time needed to fill the buffer is useful to query the GPS: each second a standard NMEA (National Marine Electronics Association) RMC (Recommended Minimum sentence C) string is recorded [11]. This string contains information of position, velocity and time. Thanks to this procedure information of vibration, position and velocity related to the same second, are associated with a single geographical point.

III. Index choice and analysis results

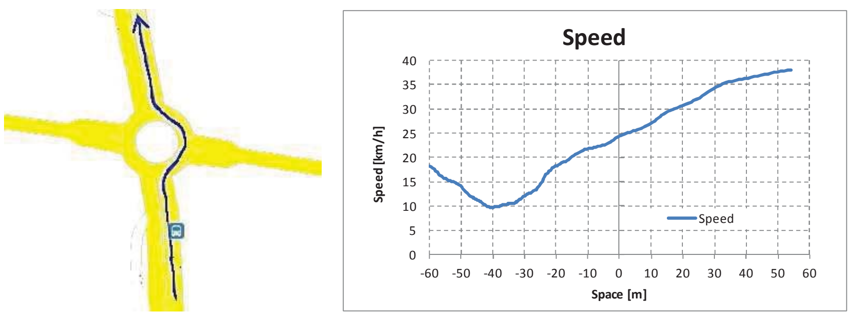
European regulation on rail transport [9] defines different type of comfort index; the one for standing passengers is called NVD. This has been adapted for road transport and it has been calculated following Equation (1),

$$NVD = 3 \cdot \sqrt{16 \cdot a_{x_W}^2 + 4a_{y_W}^2 + a_{z_W}^2} + 5 \cdot a_{y_W} \qquad (1)$$

where a_{x_W} is the RMS (Root Mean Square) longitudinal acceleration, a_{y_W} is the RMS lateral acceleration and a_{z_W} is the RMS vertical acceleration. Weighting is done following European regulations and considering human response to vibration frequency filters [9, 10]. The higher is NVD value the greater is on-board discomfort.
As said before, each second, this comfort index is linked to vehicle velocity and GPS coordinates and the results are updated to a remote database which is then queried, in order to obtain thematic maps and statistical analyses.

IV. Analysis of manoeuvres and infrastructures

Querying the developed database, cinematic parameters, such as speed and accelerations, related to vehicle vibrational comfort, can be analyzed. As a first result these parameter can be plotted as a function of position time or of position itself, as shown in Figure 2.
This kind of analysis gives detailed information strictly related to every single passage of a chosen vehicle through a considered infrastructure, that can therefore be studied very accurately. However this kind of analysis in not very suited in order to monitor a whole public transport network or to judge an infrastructure good design, because many external parameters such as driver, weather, bus crowding and traffic conditions can affect the measure. These are important factors that can be considered, for example, when discomfort causes have to be investigated.



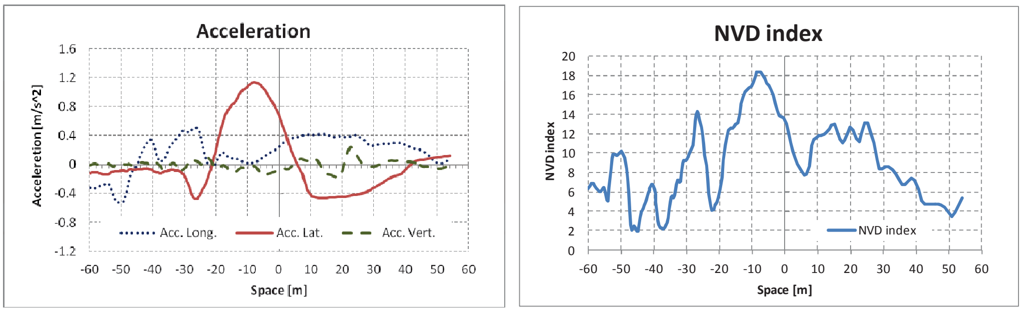


Figure 2. Cinematic parameters (speed and acceleration) and NVD index on a roundabout.

A. Geographical based analysis

In order to obtain less detailed but significant information, acquired data have to be aggregated.
A first approach consists in a geographical based aggregation obtained dividing the urban map in a grid of a chosen step (for example 1 m), and then associating to each cell the mean value of the parameter under study, in particular the NVD index. To take into account the geographical distribution of the data, the generic parameter is weighted using the inverse of the distance between the centre of the cell and the recorded position of each sample, following the widely accepted Inverse Distance Weighting method. In this way a mean value of the chosen parameter has been calculated, taking into account both geographical distribution of the data and different passages of the vehicle, in statistical different conditions, in the same geographical position.
Figure 3 shows a comfort index thematic map of a particular bus route as an average of a large number of acquisitions. In particular the bus route is superimposed on the city cartography: very uncomfortable spots (in red) as well as comfortable ones (in blue) are put in evidence.
In general, thematic maps could be very useful in order to correlate a certain physical quantity, such as vehicle speed or acceleration vector or on-board comfort, with a certain infrastructure, for example a roundabout, a speed bump or an elevated pedestrian crossing.

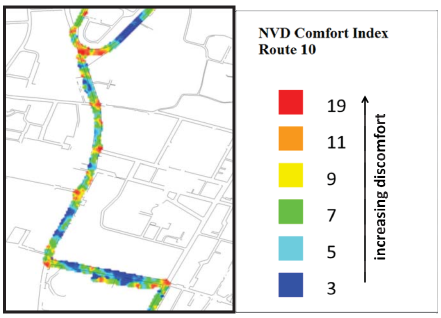


Figure 3. NVD comfort index thematic map of a portion of a bus route, superimposed on the city cartography.

B. Statistical analysis

A second approach in order to aggregate data consists in isolating some interesting infrastructures or situations, such as crossings, elevated pedestrian crossings, roundabouts, straight roads, considering the interesting physical quantities related to the infrastructure (such as vehicle speed or accelerations or on-board comfort) as stochastic variables and performing a statistical analysis.
The proposed analysis method consists of selecting a path portion with fixed length, centred on the chosen infrastructure and assessing some important statistical parameter of the distribution of the variable of interest, in particular its Probability Distribution Function (PDF), its Cumulative Distribution Function (CDF), a box plot and the 95th percentile of the distribution. This last parameter depends less on impulsive NVD index variations, non relevant from a statistical point of view, than the maximum NVD value and it has been chosen in order to summarize the whole distribution with a single number.
For example, referring to the roundabout proposed in Figure 2 and considering NDV index as a stochastic variable it is possible to study some statistical parameters, that give brief information about comfort (or discomfort) level related to the chosen infrastructure. In particular, Figure 4 shows the histogram of the distribution, the cumulative distribution and a box plot and Figure 5 represents the NVD index as a function of

the position along the path and puts in evidence (dotted line) that the 95th percentile of the NVD can be used to represent the worst on-board vibrational comfort condition when the bus goes through the selected infrastructure.

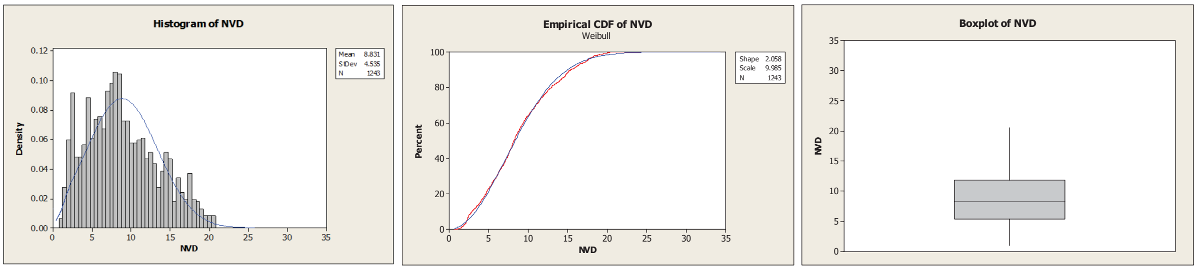


Figure 4. NVD comfort index statistical analysis.

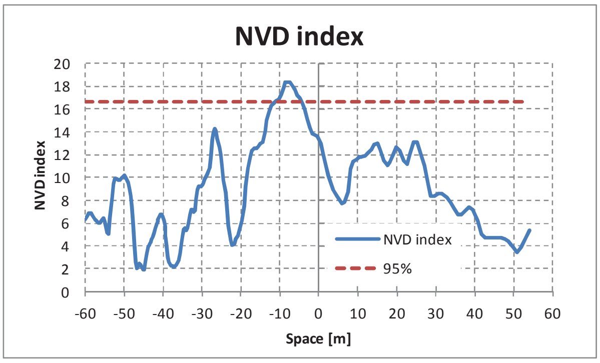


Figure 5. NVD comfort index – 95th percentile.

The whole statistical population includes all passages through an infrastructure (or through the whole route) of the same vehicle in different traffic, bus crowding, weather conditions and for different drivers. Each one of these parameters is a possible analysis criterion and a possible query for the database.
Following the described method, different statistical analyses have been performed; in particular, it is possible to represent cumulative distribution functions of comfort index of a whole bus route or of a chosen type of infrastructure, such as roundabouts, elevated pedestrian crossings or straight road. Figure 6 shows these cumulative distributions and allows to compare comfort index of the whole route with comfort index on a particular type of infrastructure, giving brief information about on-board comfort of a specific bus route and allowing for a comfort based classification of particular traffic calming devices or road infrastructures. A comparison between comfort indexes related to different types of traffic calming devices and road infrastructures is also shown in Figure 7, using box plot as statistical method.

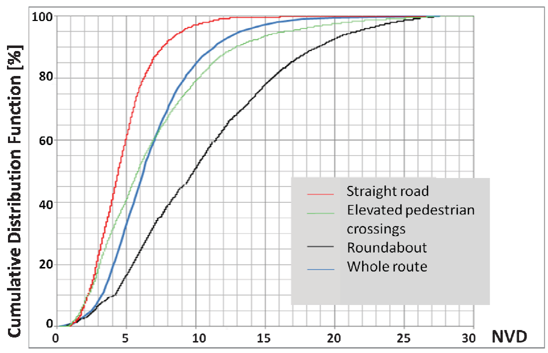


Figure 6. Comparison between cumulative distribution function of the whole route and of different infrastructures (straight roads, elevated pedestrian crossings and roundabouts) on the whole route

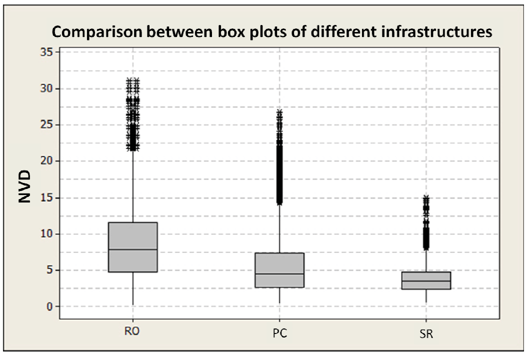


Figure 7. Comparison between box plots of different infrastructures (straight roads (SR), elevated pedestrian crossings (PC) and roundabouts (RO)) on the whole route

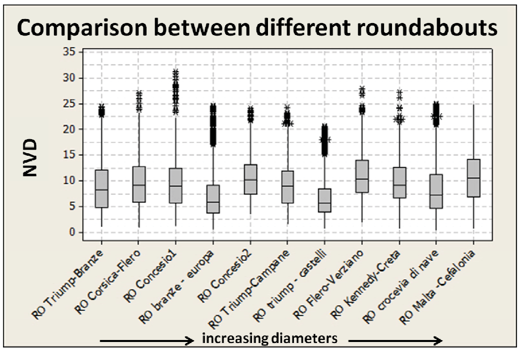


Figure 8. Comparison between box plots of different roundabouts

Figure 8 shows that it is also possible to choose a particular traffic calming device, such as roundabouts and to study comfort index distribution when bus crosses such infrastructure. The larger is the number of times when the bus goes through the selected device, the better, because the result is a more relevant statistical analysis.
In particular, Figure 8 represents the comparison between different roundabouts of the same bus route and box plot are sorted according to diameter size; data were acquired using the same model of bus. Thanks to this kind of graph it is possible to deduce if roundabouts with different diameters presents different comfort level. Another parameter that could be taken into account is the type of manoeuvre on roundabout with the same geometry.

C. Index validation

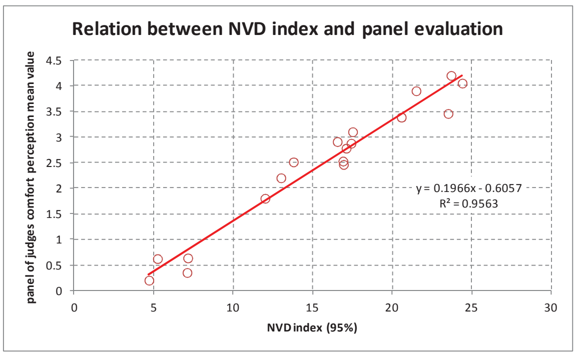


Figure 9. Relation between NVD index and panel evaluation

The NVD index related to each studied infrastructure is considered a stochastic variable and the 95th percentile of its distribution has been chosen to represent the discomfort of the considered infrastructure. To validate this choice a relation between 95th percentile and test panel opinions has been searched for [12], using the method of the simple linear regression. The test panel is composed of thirty to forty people; each person is asked to express his opinion about his perceived vibrational on-board comfort in some selected situations, for example when the

bus goes through an elevated pedestrian crossing, or a roundabout or a straight road using a score that varies from zero, when the situation is perceived as very comfortable to 4, when the situation is very uncomfortable.
The relation found between 95th percentile of the NVD distributions and test panel opinions is shown in Figure 9 and it could be used, as proposed by the authors, to define threshold values for comfort index.

IV. Conclusions

A portable and autonomous measuring device for on-board comfort measurements on local transport buses has been set up and a specific software for retrieving from multiple devices, stocking and localizing data on the whole local transport network has been created.
Automated tools for a geographical analysis of collected data with a standard GIS interface have also been developed and statistical analysis of the influence of specific traffic calming devices on on-board comfort was made feasible thanks to data collected. Moreover correlations between infrastructure geometry and on-board comfort have been made possible.
In particular, the proposed analysis methodology permits, thanks to comfort thematic maps, to identify critical points, geographically localized, on a particular route, making possible a fast maintenance work if needed or pointing out comfort problem related to traffic calming devices or particular traffic and infrastructure conditions.
Using comfort cumulative distribution functions or box plots it is possible to compare different bus routes, or different types of infrastructures, or different type of bus travelling on the same route, or different infrastructure of the same type that differs from geometry or for crossing manoeuvre.
Systematic acquisition of data regarding the whole transport network of a chosen area could allow to monitor temporal evolution of vibrational comfort of the road network that is related to traffic conditions, road surface damages, presence of traffic calming devices. In this way, all these variables temporal development can be monitored as well as public transport system general appeal and interactions between subsequent traffic calming devices or road infrastructures.
Another possible further application is vehicle predictive maintenance, considering comfort level of a bus as a function of bus usage and wear. Comfort level of the same bus can be monitored as a function of usage time; an increasing value of discomfort level can be a clue about maintenance state.

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