PRACTICAL IMPLEMENTATION OF NOTHING-ON-THE-ROAD BRIDGE WEIGH-IN-MOTION SYSTEM

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ABSTRACT

Bridge Weigh-in-Motion (B-WIM) is a method of using instrumented bridges to weigh passing heavy vehicles. Accurate vehicle velocity and axle spacing determination are crucial for accuracy of weighing results.

The paper explains the basic B-WIM principles including the different methods of obtaining speed and axle spacings that are used in the SiWIM B-WIM software. In previous generations of B-WIM systems these values were obtained from axle detectors that were attached to or built into the road surface. The new generation of SiWIM B-WIM system uses signals from additional strain transducers, mounted underneath the bridge.

The basic Nothing-On-the-Road (NOR) algorithm used in SiWIM calculates correlation between two time-shifted signals from these additional strain transducers. The position of the peak in the correlation function of the two signals determines the time-shift between signals and thus the vehicle velocity. Aside for determining truck position on the bridge, the accurate velocity is also used in other parts of the B-WIM algorithm to determine the number of axles and the distances between them.

In some cases the correlation method fails due to asymmetry of influence lines (characteristics bridge deflection under the moving load) or due to its negative values. This can happen on multi-span bridges and on fixed-supported (integral) bridges where bending moments due to the traffic loading are transferred from the superstructure to the supports. The paper will demonstrate how to correct these problems. The procedures include estimating the negative part of the influence line and removing it from the signal as well as identifying the matching axle peaks from the signals to obtain accurate vehicle velocity.

Results show that the modified NOR algorithm correctly detects vehicles not only on simply supported, but also on integral and multi-span bridges.

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1 INTRODUCTION

The need for knowing real traffic loading is essential for efficient road maintenance. This data can be obtained with different WIM (Weigh-in-Motion) systems, either pavement or bridge type. While the pavement systems use weighing sensors installed into the pavement, the bridge WIM (B-WIM) system uses instrumented and calibrated bridge superstructures that act as weighing scales (Moses 1979, Žnidarič et al. 1999 and 2002). B-WIM was extensively studied in mid 1990's in two European projects: the COST 323 action "Weigh-in-Motion of Road Vehicles" and especially in the Work Package 1.2 of the European 4th Framework research project "WAVE – Weighing of Axles and Vehicles for Europe" (WAVE 2001). Since then research continued individually in several countries around the world. In Slovenia, the prototype Slovenian WIM (SiWIM, "Si" being the ISO country code for Slovenia) system from WAVE evolved into a standalone product which is constantly being improved and upgraded.

Until recently all WIM systems required special sensors for detecting axles of the vehicles and consequently, for calculation of their velocity. This data is also needed to classify vehicles and to calculate their axle loads and gross weight.

2 AXLE DETECTION IN WIM SYSTEMS

Number of axles, axle spacings and velocity of a vehicle are the required information when calculating axle loads with any WIM system. For this purpose at least two sensors, separated by a known distance are needed in each driving lane. Axle detectors (ADs) can be used either exclusively for detection of axles or perform this job as a part of weighing procedure. The common types of axle detectors are inductive loops, pneumatic hoses, tape switches, fibre optic sensor or even less accurate weighing sensor, such as piezo-ceramic bars. The main disadvantage of all axle detectors, especially those for permanent setups, are the installation and maintenance procedures, which cause considerable traffic delays. Sensors also deteriorate over time.

A major advantage of bridge WIM is its portability, i.e. its feature that the entire system can be moved quickly from one site to another to collect representative samples of traffic data during short-term, 1 to 2 week measurements. In such cases also the axle detectors can be exchangeable, with rubber hoses stretched across the pavement being the most popular selection (Figure 1, left). They are cheap and efficient and provide, with appropriate signal conditioning, sharp peaks for individual axles. The first generation of bridge WIM systems used mechanical tape switches (Figure 1, right), but they have proved unreliable and more difficult to install. A promising alternative are the axle detectors based on optic-fibre technology, but they have not been tested with a bridge WIM system yet.

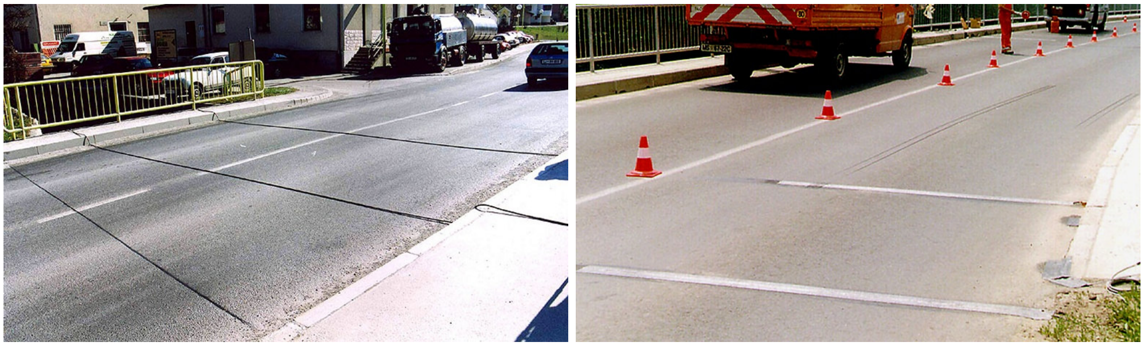

Figure 1 - Axle detectors: pneumatic tubes (left), tape switches (right)

To eliminate all actions on the pavement and, consequently, to improve durability of WIM systems, to decrease costs of installation and to reduce inconvenience to the road users, the WAVE project introduced FAD, the Free-of-Axle Detector bridge WIM which processes the required axle information from the measured strain recordings. First successful demonstrations were made on orthotropic deck bridges (WAVE 2001) and on short slab bridges (Žnidarič et al., 2002). Yet, to be reliable under any road, bridge and traffic conditions, the FAD, also known as NOR (Nothing-On-the-Road) bridge WIM systems, required substantial further developments.

3 TYPES OF BRIDGES USED IN NOR B-WIM

In a NOR B-WIM system the information from conventional axle detectors is replaced by the signals from the strain transducers attached to the bottom side of the bridge superstructure. These transducers can be either those already used for weighing or some additional ones placed in locations where sharp axle peaks can be recorded (WAVE 2001).

Not all bridges are suitable for NOR installations. As the bridge span length is practically always longer than the short axle spacings, the measured strain signals always represent joint contributions of several axles that are on the bridge at the time. The more axles on the bridge, the more difficult it is to identify the axle spacings. Thus, the ideal NOR bridges are either short or have secondary elements that divide the main span into shorter “sub-spans”, such as cross-beams or cross-stiffeners (see the examples below). Thicker superstructures smear the individual peaks in the signal, which makes axle identification more difficult.

WAVE project started to develop the NOR algorithms on the orthotropic deck bridges, which have very thin steel deck and cross-stiffeners at every 3-5 meters. This is ideal for NOR as individual axles are clearly seen in the signal and rather simple algorithms can identify axles from the strain signals. Yet, as these bridges are scarce, other “less-ideal” bridges were investigated to raise the practical value of the method. WAVE therefore suggested to install NOR on 6 to 10 meter long slab bridges, with as thin slabs as possible (usually 0.5m to 0.8m thick). If pavement was smooth (there was no bump on the approach to the bridge), encouraging results were obtained, with most of the axles identified (Žnidarič, 2002). However, a universal algorithm that would work on most “real life” structures, with correct identifications success rate of 99% and above, required a considerably more robust algorithm.

3.1 Sample strain signals

Figure 2 demonstrates appropriateness of different types of bridges for NOR. Each example is illustrated with a photo and a typical response of the structure during a passage of a conventional fully loaded (40 tones) 5-axle tractor semi-trailer, with two single axles and one triple axle.

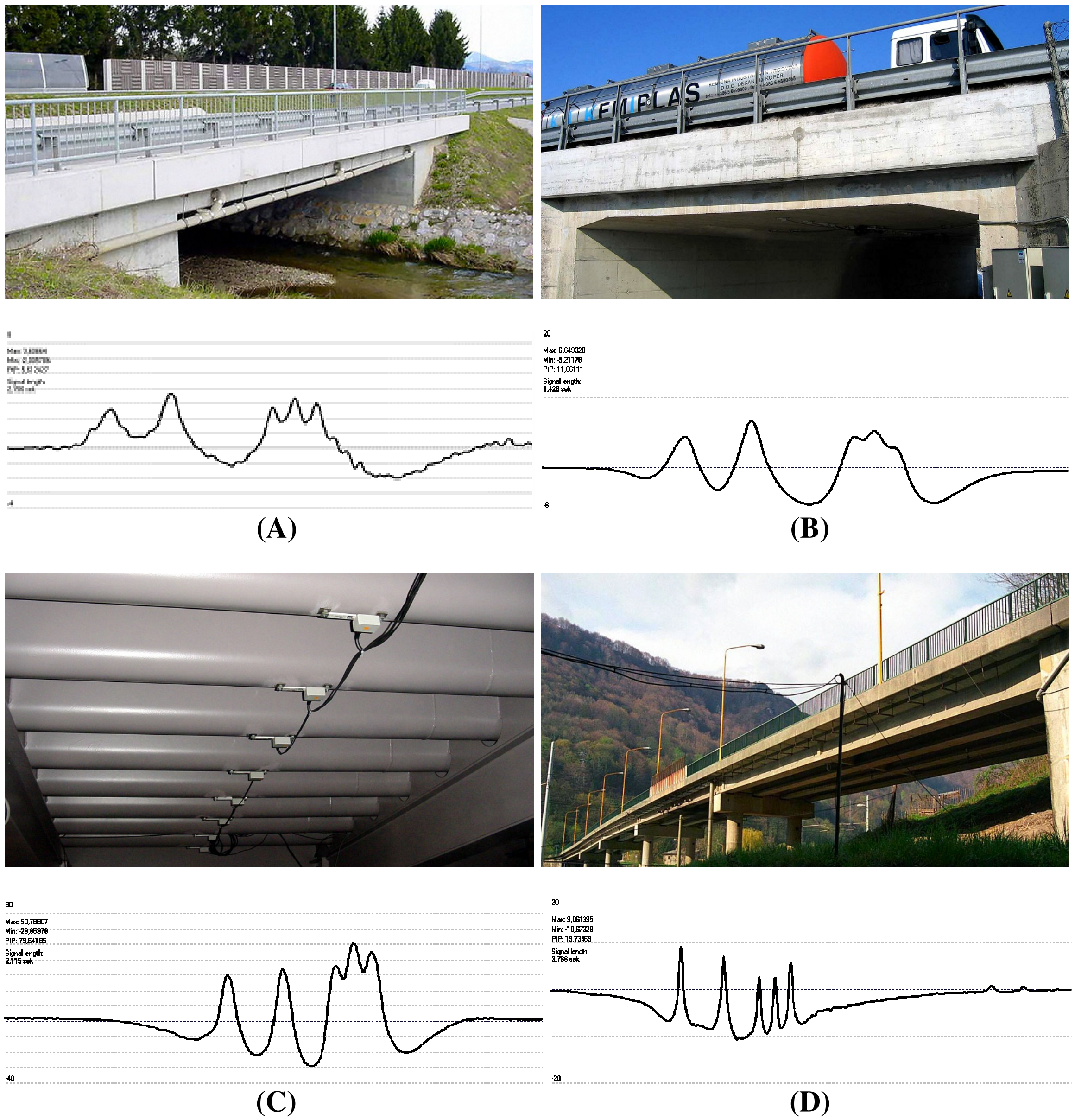

Figure 2 – (A) - Bridge with high dynamics; (B) - Bridge with 0.8m thick slab; (C) - Orthotropic-deck bridge; (D) - Beam-deck bridge instrumented on the slab between the beams

(A) If the bridge is thin and longer and its eigenfrequencies match those of heavy vehicles or there is a bump on the road just before or on the bridge, the pronounced dynamics of the vehicle-bridge interaction imposes additional peaks into the signal, often with a frequency that is in the range of shorter axle spacings. If and to what extent they appear depends on characteristics of the vehicle, its weight and speed. Such peaks must be ignored and not treated as axles. The response is of a fully loaded 5-axle tractor semi-trailer over a 12m long and 0.5m thick slab bridge.

(B) If the superstructure is stiff and smooth, as was the 6m long integral bridge with a 0.8m thick slab, there will likely be no dynamics, but peaks from individual axles, especially axles from a group, can be smeared and difficult to find.

(C) WAVE already identified the orthotropic deck bridges (bottom-left) as suitable for NOR installations. Indeed, results from a bridge near Warsaw in Poland, which was instrumented for a week in the scope of the European Commission 5th Framework project SAMARIS (Žnidarič et al., 2004), confirmed that this can be done without any major constraints. The bridge had 6 spans with total length of over 500m. The strain transducers were installed on the deck stiffeners laying on the transverse cross-beams spaced 2.5m apart from each other. Position close to the first pier was used to reduce the effects of global deflections of the measured span.

(D) The recent research and tests confirmed that, with some restrictions, NOR can also be used on longer beam-deck bridges, as was the one with six 30.5m long simply supported spans. The strain transducers for detecting axles were attached to the slab between two beams, close to the cross-stiffener at the mid-span. It is interesting to observe that the individual peaks are even sharper than those measured on the orthotropic deck bridge.

Except in example D, the middle axle in the triple axle always seems to generate the highest response. This is due to the fact that the total response measured on a bridge is in fact a sum of responses of each individual axle. If the influence line (bridge response to a single axle unit load) is wide, compared to the distance between axles in an axle group, the response at the position of the middle axle is a sum of three appreciable components: (a) peak of the middle axle response, (b) trailing slope of the first axle response and (c) leading slope of the third axle response. The responses at the position of the first and last axle are, however, composed of only two appreciable components: (a) peak of the axle in question and (b) leading or trailing slope of the middle axle response. From this it follows that the total response at the position of the middle axle is higher than the response at the position of the first or last axles, even if the actual axle loading is the same.

4 SIWIM SYSTEM AND NOR B-WIM

The SiWIM was introduced during the WAVE project which as one of its deliverables produced a software prototype of a bridge WIM system. Since then the SiWIM has undergone significant changes. The first 2 versions, developed between 1999 and 2002, mainly improved the hardware, reliability of the basic bridge WIM algorithm and user-friendliness of the software. Subsequently, the main efforts in the last 4 years were oriented towards:

- extension of its application to bridges not being recommended by WAVE yet, such as beam-deck bridges over 20m in length,
- development and implementation of the NOR measurements and
- increasing number of successful weighing on less ideal bridges by implementing recursive methods which in an 'intelligent way' correct errors due to bad measurements (i.e. as a result of bridge-vehicle dynamics, multiple presence of several vehicles on the bridge, errors of axle detectors etc.).

5 ADVANCED NOR B-WIM ALGORITHM

As stated above, the main challenge in the area of NOR was to increase the number of successful vehicle identifications, especially on the less appropriate structures.

5.1 Speed determination

The first step in a NOR algorithm is to determine the vehicle velocity. The WAVE project proposed to calculate it from the time difference of peaks from the strain signal (WAVE, 2001). This gave satisfactory results on "ideal" bridges that generated sharp strain peaks under the axles but caused major problems on the less ideal bridges with pronounced dynamics (with too many peaks) or with longer and thicker superstructures (with smeared peaks), such as examples A and B in Figure 2. Calculation of a correlation function has proven to give more robust results. The algorithm correlates speed strain transducer signals $f(t)$ and $g(t)$ recorded at two different longitudinal positions, using the following expression:

$$Corr(f, g)(t) = \int_{-\infty}^{+\infty} f(\tau) g(t+\tau) d\tau \qquad (1)$$

In the SiWIM system the calculation of the correlation function is performed with the help of a Fast Fourier Transform and the discrete correlation theorem (Press et al. 1992). Both signals are Fourier transformed, the transforms multiplied and the inverse transformation performed on the product. The result is the discrete correlation function between the signals.

Even if shapes of both signals do not entirely match, the value t_0, defined as the value of t at which the maximum value of the correlation function occurs, corresponds well to the time difference between the two measured signals, if the influence line (bridge response to a single axle unit load) is symmetric.

Figure 3 shows an example of signals f (blue) and g (magenta) and their correlation function (green), where the t_0 is marked by a vertical line through the correlation function maximum. Once the t_0 has been determined, the speed of the vehicle is easily determined from the known distance between the speed determination transducers.

Figure 3 - Speed determination signals and their correlation

The actual distance between speed determination transducers depends on many factors, including bridge length and thickness, type of structure,… Generally speaking, one of the sensors should be mounted at around 20%-40% of the span and the other at around 60%-80% of the span. The distance between them should be around 4m, although it can be as low as 2m or, in exceptional cases, 1.5m. However the accuracy of speed determination is lower, if the sensors are closer to each other.

5.2 Axle determination

Appropriate filtering is crucial for signals with a large dynamic component or when axles in a group are smeared, as is the case on thick slab bridges. Since the speed is known at this stage, the filtering is performed in the space domain, by averaging data over a certain length. The axle determination sensor need not be the same as one of the speed determination sensors. Indeed, it is better to select a sensor that is located directly beneath the wheels, where the signals are the strongest and have the most pronounced peaks.

The signal is filtered twice with a low-pass filter, once with a filter length of 1.3m (the largest axle distance in a group of axles) thus discarding all dynamics and axles and once with a filter length of 0.6m (the shortest distance in a group of axles), thus discarding dynamics and keeping axles (these figures can be changed to fine-tune the algorithm to the bridge). The filtered signals are then subtracted – in effect performing band-pass filtering – and the difference is then searched for axles. Figure 4 shows the measured axle signal and the difference of filtered signals of a 5-axle vehicle. One can see that, while the axles in the triple-axle group are indistinguishable from each other in the measured signal, they can be clearly seen in the difference of filtered signals.

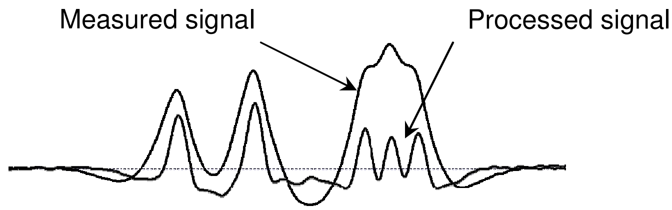

Figure 4 - Measured and processed signals of a 5-axle vehicle

The difference of filtered signals is searched for peaks, which correspond to axles. The signal is first split into groups of axles (containing either a single axle or multiple axles) with the use of a threshold value. The groups are then searched for individual axles using a different threshold. If there are light vehicles on the bridge (as seen in the tail of the bridge response in example D on Figure 2), they are identified by another threshold. An axle position is defined as the position of the peak. Once axle positions have been identified, they are written into channels used for axle detectors. From then on the SiWIM system proceeds as though axles were identified with axle detectors, so in effect the NOR module is a signal pre-processor for a “classical” B-WIM system with axle detectors.

6 CORRECTIONS TO NOR B-WIM ALGORITHM

There are at least two cases in which the above described algorithm fails to work. Sometimes the speed determination signals have a pronounced positive or negative static component. When the static component is either positive or a negative simultaneously on both sensors, the peak corresponding to t_0 in the correlation function is falsely determined. Axle determination in case of a negative static component is also adversely affected, as even very pronounced peaks in the axle determination signals can lie below the appropriate threshold. This situation can occur on multi-span bridges and on fixed-supported (integral) bridges where bending moments due to the traffic loading are transferred from the superstructure to the supports.

The other problematic case is when the speed determination signals are asymmetric. This typically occurs on shorter bridges, where, in order to achieve appreciable distance between speed determination sensors, one is forced to place them near the supports. The result is an inaccurate determination of t_0.

The basic correlation algorithm in the SiWIM system has been extended to cope with both of these by performing additional processing on speed and axle determination signals.

6.1 Static components in speed determination signals

Figure 5 shows an example of such speed determination signals and the resulting correlation function. One can see that the hump in the middle is larger than the peak corresponding to t_0, thus precluding a simple search for a maximum.

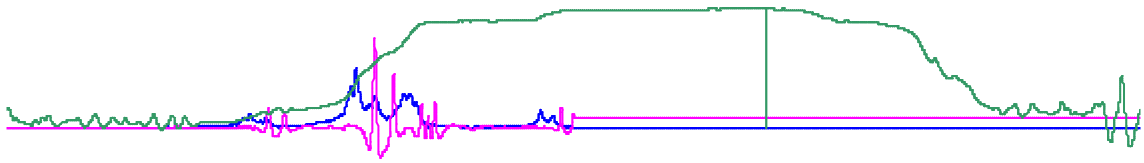

Figure 5 - Correlation function in case of large static component

Fortunately the solution is relatively simple, since the hump is always located in the middle between 0 and t_{max} (the right-most point in correlation function). The values of the correlation function at 0, $1/3t_{max}$, $2/3t_{max}$ and t_{max} are evaluated and the polygon formed by these points is subtracted from the correlation function.

Figure 6 shows the result of such a procedure. The correct value of t_0 is now easily determined.

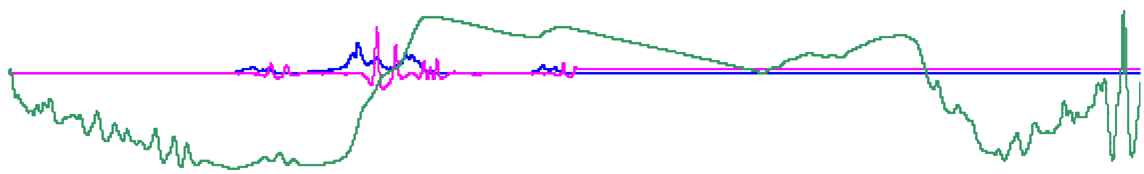

Figure 6 - Corrected correlation function

6.2 Negative static component in the axle determination signal

To solve the problem of negative static component in the axle determination signal, a more elaborate procedure is needed, where the negative part of the signal is estimated by constructing an envelope of the signal. This is done by finding the minima of the signal and constructing a polygon through the minima. Since the signals are, in practice, always burdened with dynamics and/or noise, it makes no sense to search for all local minima, as the processing load would be quite high. Thus we need to introduce *qualified extrema.*

A maximum is considered a qualified maximum if there are points both to the left and to the right of it, both of which must be at least some value δ below it. Similarly, for a qualified minimum, there must exist at least two points that are at least δ above it. This effectively ignores all local extrema whose "amplitude" is less than δ. The value of δ is usually chosen as 20% of the difference between global maximum and global minimum. This finds enough qualified minima to construct a polygon through them such that the negative component is eliminated.

This correction is still in the implementation and testing phase, so there have been no field measurements performed with it. However, on test cases, taken from sites where it has been difficult to set up parameters to reliably determine axles, the preliminary results are promising.

6.3 Asymmetric speed determination signals

Qualified maxima are also used when correcting for asymmetric speed determination signals. The problem lies in the fact that the correlation function has a maximum where the two correlated functions are shifted by such an amount as to maximise the overlapping *area*. This works well for determining peaks if the influence lines are symmetric, since the peaks are located in the middle of the hump. However, when the signals are asymmetric, the distance between peaks is not the same as the value t_0 obtained from correlation.

To correct this, the qualified maxima of each speed determination signal are found, with δ again being equal to 20%. The times of the first two maxima (arising from the passage of first axle over each sensor) could in principle be subtracted and the resulting value used for the calculation of speed. However, the signals at this stage are not yet filtered to enhance axle peaks as vehicle speed is required to transform the signals into the space domain and enable length-based filtering. Thus the first axle sometimes fails to generate a peak that would be pronounced enough to register as a qualified maximum. The algorithm would then erroneously use, for example, the time difference of the peak from the first axle on one sensor and the peak from second axle on the other sensor.

To rectify this we use the first few qualified maxima (usually 2 or 3) from both channels. The t_0 obtained from correlation is used as a reference and the time differences of each of the 4 (or 9) pairs of maxima are compared to it. The pair whose time difference is the closest to t_0 is then chosen as the one from which the speed is calculated.

Figure 7 shows the result of such a procedure. The vertical line representing the corrected time difference is to the left of the correlation peak. This means that the correct time difference is larger than the value calculated from correlation, as one would expect from the asymmetry.

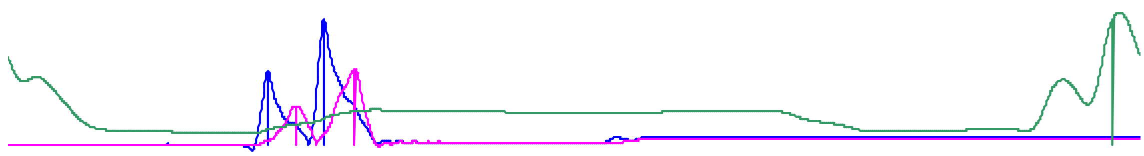

Figure 7 - Correlation and correction of asymmetric speed determination signals

7 RESULTS – IDENTIFICATION OF AXLES AND VEHICLES

Efficiency of the new NOR axle detection was tested on 2 extreme cases from Figure 2, on the thick slab with smeared peaks and on the beam-deck bridge with distinct peaks. In the first case, example B in Figure 2, a one hour video of all traffic was recorded and was visually compared to the NOR results calculated by the SiWIM system. Detailed analysis showed (Table 1) that from the 202 heavy vehicles recorded on the tape, 182 or 90.0% had the correct number of axles, but the axle distances varied for up to 15cm, which for 19 (additional 9.5%) of these 182 vehicles meant that they were not correctly classified. Three heavy vehicles from the tape were not found in the results, and three non-existent vehicles were identified as a result of noise in the signal. Most of these problems, primarily caused by light, unloaded vehicles, will be mitigated with the next generation of the SiWIM software, currently in development and testing. It will remove such errors automatically by correlating the measured and the modelled bridge responses. SiWIM already calculates a correlation factor between the measured and the modelled signals which indicates incorrect number of axles, but automatic corrections of the result is not yet being used.

Table 1 - Incorrectly identified vehicles and axles on a thick slab bridge

Incorrectly identified	Missed	Added
Complete vehicle	3 (1.5%)	3 (1.5%)
1 axle	7 (3.5%)	2 (1.0%)
2 axles	4 (2.0%)	1 (0.5%)
3 axles or more	0 (0.0%)	0 (0.0%)
Total	14 (6.9%)	6 (3.0%)

Results from the beam-deck bridge with instrumented slab between the beams (example D in Figure 2) were considerably better. It should be noted that the initial SiWIM installation on this bridge used axle detectors (ADs). The NOR sensors were added later during the measurements and, consequently, NOR results were obtained entirely by post-processing of the stored strain data, *as triggered by the axle detectors*. One of the ten days of measurements was analysed. In that day the axle detector system weighed 260 vehicles with the gross weight above 5 tons. The NOR algorithm weighed 261. One vehicle was not detected, because it was driving on the other lane where there were no NOR sensors. On the other hand, 2 additional vehicles not identified with the AD system were captured (there can be more closely spaced vehicles stored in one file). This number would probably be even higher during real-time measurements because if the AD system misperformed, no files were saved and thus NOR processing was not possible. Furthermore, from all axles of the 261 vehicles the NOR algorithm missed only one single axle. It belonged to a very light trailer.

8 CONCLUSIONS

Instead of different types of axle detectors, the bridge WIM systems can often use strain sensors located underneath the bridge to detect axles. This method is known as NOR (Nothing-On-the-Road) or FAD (Free-of-Axle Detector) bridge WIM system.

With the recent developments the number of different types of bridges suitable for NOR increased and includes slab bridges, beam-deck bridges and orthotropic deck bridges. The variety of bridge types produces a variety of shapes of strain signals used for detecting the axles. They can have a high dynamic component in the measured signals or can produce heavily smeared signals which make individual, especially light axles difficult to locate.

A new algorithm which deals with most types of strain signals was developed. It first correlates signals from two strain transducers, mounted at different longitudinal positions, to obtain the vehicle velocity. Band-pass filtering is then applied to extract the individual axle positions.

For “difficult” bridges, where the simple correlation fails due to static component in the signals, corrections that either eliminate the static components or correct its effects on the correlation function were developed and tested.

Comparison to the videotaped traffic showed that the identification rate was good even on the bridge with the highly smeared signals. On such bridges the original NOR method, proposed in WAVE, would successfully identify only a few multiple axles. On the other hand, the experiment on a beam-deck bridge (Žnidarič et.al. 2005) showed that by combining high accuracy of GVW results with the NOR signals, accuracy of results was greatly improved.

Consequently, in Slovenia around 20 bridges on regional roads (almost 50% of all such bridges instrumented for WIM in 2005) have been instrumented without axle detectors and this number is growing. Additionally, *all* of SiWIM installations on Slovenian highways have been of the NOR type.

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