Master Thesis

Tor Holm Slettebak

May 23, 2016

1 Preface

Contents

2 Introduction

Random citation [1] embeddeed in text. Random citation [1] embeddeed in text.

3 Theory

3.1 Bridge Weigh-in-Motion

A Bridge Weigh-in-Motion system is based on measurements of a bridge's deformation. The BWIM system uses these measurements to calculate passing vehicles axle loads. There are different approaches to assembling such a system, but they typically consists of a strain gauge measuring the strain induced by passing vehicles, a axle detector used to find the vehicle speed and spacing of axles and a computer or data storage device. An algorithm then is able to use the data gathered from the axle detector and strain gauge to calculate axle loads [5].

3.1.1 Moses' Algorithm

Moses' algorithm is based on the fact that a moving load along a bridge will set up stresses in proportion to the product of the value of the influence line and the axle load magnitude. The influence line being defined as the bending moment at the point of measurement due to a unit axle load crossing the bridge [5].

Moses' algorithm is built from the fact that a moving unit load on a bridge will induce stresses proportional to the product of the value of the influence line and the axle load magnitude.

Each individual girder's stress is related to moment:

$$\overbrace{\sigma_i}^{\text{stress in i'th girder}} = \frac{\overbrace{M_i}^{\text{bending moment i'th girder}}}{\underbrace{W_i}_{\text{section modulus}}} \tag{1}$$

Expressing the moment in terms of strain gives

$$M_i = W_i\sigma_i = \overbrace{E}^{\text{Modulus of elasticity}} \times W_i \times \underbrace{\varepsilon_i}_{\text{strain in i'th girder}} \tag{2}$$

The sum of the individual girder moments is therefore:

$$M = \sum_{i=1}^{N} M_i = \sum_{i=1}^{N} EW_i\varepsilon_i = EW\sum_{i=1}^{N}\varepsilon_i \tag{3}$$

The sum of the girder strains is proportional to the gross bending moment. The total bending moment and the measured strain is thus directly related by EW. These constants can be calculated through the bridge's dimensions and material properties. However through measuring the effects of a known vehicle passing the bridge these constants can be derived.

Weigh in motion is an inverse type problem, the strain is measured and the cause of the strain is to be calculated. The theoretical bending moment corresponding to axle loads on the bridge at one strain sample, is given by:

$$M_k^T = \sum_{i=1}^{N} A_i I_{(k-C_i)} \tag{4}$$

$$C_i = (L_i \times f)/v \tag{5}$$

Where:

N = *the number of vehicle axles*

A_i = *the weight of axle i*

I_{k-C_i} = *the influence line ordinate for axle i at sample k*

L_i = the distance between axle i and the first axle in meters

C_i = *The number of strain samples corresponding to the axle distance* L_i

f = the strain gauge's sampling frequency, in Hz

3.2 Influence lines

For a B-WIM system the influence line is defined as "the bending moment at the point of measurement due to a unit axle load moving along the bridge [4]". The influence line could be found through assembling a model of the bridge in any CAD or frame-program, this would however take a lot of time especially for more advanced bridge's. Depending on the support of the bridge the influence lines takes different theoretical forms, as seen in Figure 1. The true influence line for a bridge lie somewhere in between the simply supported and fixed version [4, p. 146]. Influence lines is a big source of error in a B-WIM system.

Znidaric and Baumgärter [4], did a study on the effect of choice of influence line. This study shows errors up to 10% for a short 2 m bridge span and errors of several hundred percent for a 32 m bridge span. This underlines the importance of using correct influence lines for a B-WIM system.

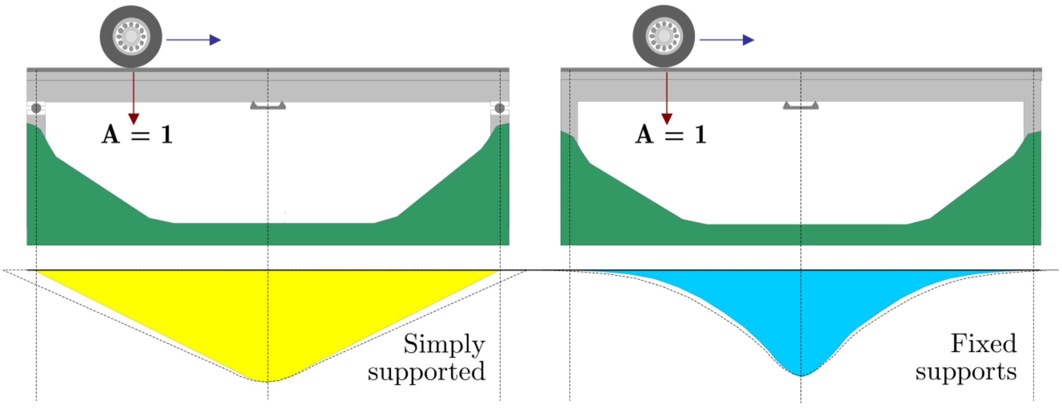


Figure 1: Influence lines for simply and fixed supported bridges, figure from [5]

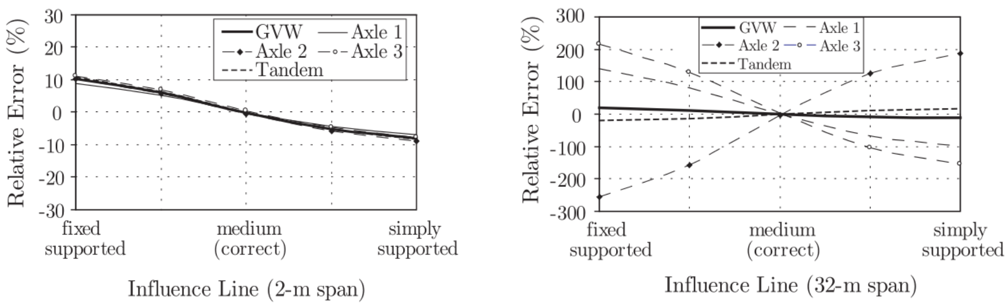


Figure 2: Errors of axle loads due to wrongly selected influence lines, figure from [5]

3.2.1 Matrix method

Quilligan [5] developed a 'matrix method' to calculate the influence line of a bridge through the measured strain induced by a vehicle. This method is derived from Moses', equation 6.

$$Error = \sum_{k=1}^{K} [\varepsilon_k^{measured} - \varepsilon_k^{theoretical}]^2 \tag{6}$$

Equation 6 were originally used to filter out the dynamic response of the bridge. The theoretical strain in this equation can be expressed as a product of axle loads and influence ordinates at sampling points, see equation 4, thus we can expand equation 6:

$$Error = \sum_{k=1}^{K} \left[\varepsilon_k^{measured} - \left(\sum_{i=1}^{N} A_i I_{(k-C_i)}\right)\right]^2 \tag{7}$$

The set of influence ordinates I that minimizes $Error$, forms the wanted influence line.

$$\frac{\partial Error}{\partial I_R} = \frac{\partial \sum_{k=1}^{K} \left[\varepsilon_k^{measured} - \left(\sum_{i=1}^{N} A_i I_{(k-C_i)} \right) \right]^2}{\partial I_R} \tag{8}$$

For a given number of known axle loads this equation comes down to a set of $(K - C_n)$ number of linear equations. Rearranging the equations and writing them in matrix form leads to:

$$\left[AxleMatrix \right]_{K-C_N,K-C_N} \left\{ I \right\}_{K-C_N,1} = \left\{ M \right\}_{K-C_N,1} \tag{9}$$

Where:

$\left\{ M \right\}$ = a vector depending on axle weights and measured strain, $M_{i,1} = \left(\sum_{j=1}^{N} A_j \varepsilon_{(i+C_j)} \right)$

$\left[AxleMatrix \right]$ is a matrix depending only on the axle loads, defined by equation 10.

$$\left[AxleMatrix \right] = \sum_{i=1}^{N} \sum_{j=i}^{N} \left[AxleMatrix \right] + \left(A_i A_j \left[Diagonal \right]_{C_j - C_i} \right) \tag{10}$$

Which produces the upper triangle of the symmetric AxleMatrix. Where:

$\left[Diagonal \right]_{C_j - C_i}$ = a diagonal matrix of ones, where diagonal is placed with an offset, $C_j - C_i$, from the center matrix diagonal.

Solving equation 9 for the influence ordinate vector gives the influence line for the strain history. This can be done through inversion of the AxleMatrix (equation 10) or other numerical solutions like a Cholesky factorization.

3.2.2 Optimization

testing [2]. For this thesis one of the goals where to assess the accuracy of and optimization algorith for finding a bridges influence lines. To develope such an algorithm test strain signal where produced by a matlab script, and the algorithm developed was to find the influence line used to produce the strain signal. In theory using optimization to identify influence lines should work well, and indeed it did for these produced theoretical strain signals.

3.3 Finding the train's speed

3.4 The axle distances

3.5 Filtering and noise

All signals are subjected to noise, which can be defined as

> unwanted disturbances superposed upon a useful signal that tend to obscure its information content [6]

Noise in a BWIM system can be intrinsic noise, that is noise generated inside a system, and extrinsic noise which is noise generated outside the system. A train approaching the BWIM sensors may be a source of extrinsic noise. Performing bridge weigh-in motion relies upon the information provided by the sensor signals. When distance between detected axles is to be found, noise is a source of distortion which may increase error of found distance, it may also make it difficult for the program to detect the desired peaks in the signal. Smoothing the signal is therefore completely necessary for a BWIM system. During the developement of the software for this thesis, several attempts on finding and using appropriate filters have been made. Matlab contains many such filter functions which can be used, such as a Butterworth and SGOLAY filters.

3.5.1 Noise smoothing through fourier transformation

The following quotation from Matlabs: Practical Introduction to Frequency-Domain Analysis, see [3], describes how frequency analysis can be done with Matlab. (badly written!!)

> Frequency-domain analysis shows how a signal's energy is distributed over a range of frequencies. A signal can be converted between the time and frequency domains with a pair of mathematical operators called a transform. An example of this is the Fourier transorm which decoposes a function into the sim of a number of sine wave frequency components. The 'spectrum' of frequency components is the frequency domain representation of the signal. The inverse Fourier transform converts the frequency domain function back to a time function.

Performing a fast fourier transformation in matlab on a vector signal, gives the oportunity to remove unwanted frequencies from the signal. When the signal is transformed into the frequency domain, setting all the frequencies above 30 Hz to zero and then transforming the signal back into the time domain would smooth a typical BWIM signal greatly.

4 Method

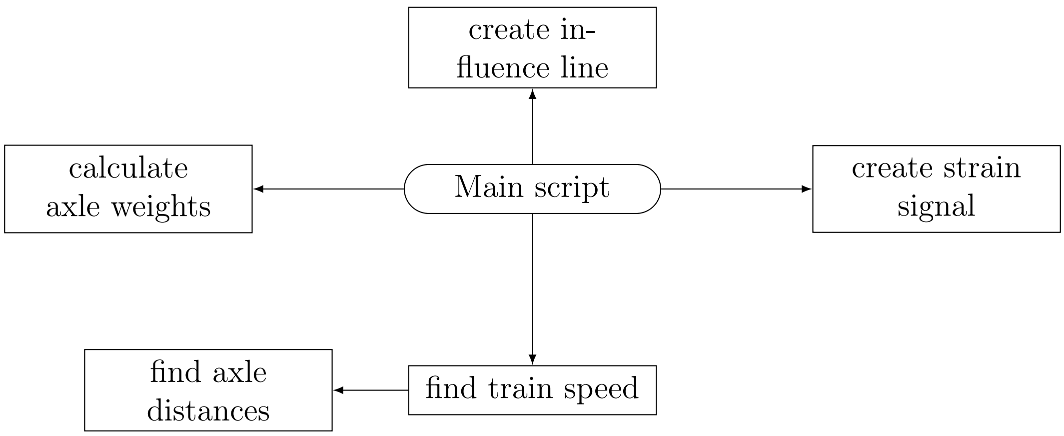
4.1 Programming a BWIM system

Describe shortly how the BWIM system have been programmed. Keywords:

- Beam bridge model
- Producing a strain history through influence lines
- Finding the speed of the train
- Finding Axle distances
- Solving system for axle weights

This master project began by learning how a BWIM-system works, and to then create a working model performing BWIM. To not make this a too big project this meant building a simple beam model of a bridge in Matlab, and simulate moving loads crossing it.

A simple flow diagram describing the intial BWIM program:



4.1.1 Producing a strain signal

Through the theoretical moment influence lines of the beam, a strain signal can be built through the moment-strain relationship, found in equation3, for a given set of axle weights. A simple beam bridge model, as seen in figure 3, will not recreate a actual bridge strain signal but will be used to create a working BWIM system. The produced strain signal will differ from an actual strain signal mostly because of dynamics, from the train and bridge, and because actual boundary conditions of a bridge will differ from the boundary conditions of a simple beam model. The strain sensors will also produce noise distorting the signal.

To make as good a signal as possible, some effort were placed into recreating the effect mentioned above. To add noise to the signal, white gaussian noise was included in the signal through Matlabs wgn function "http://se.mathworks.com/help/comm/ref/wgn.html".

This strain signal could then be used as a base to build the code for a BWIM system.

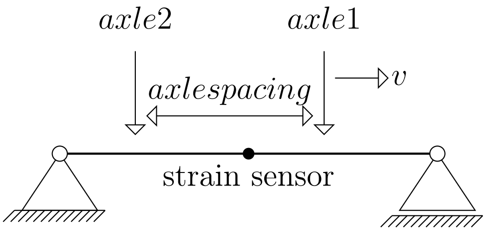


Figure 3: Beam model for developement

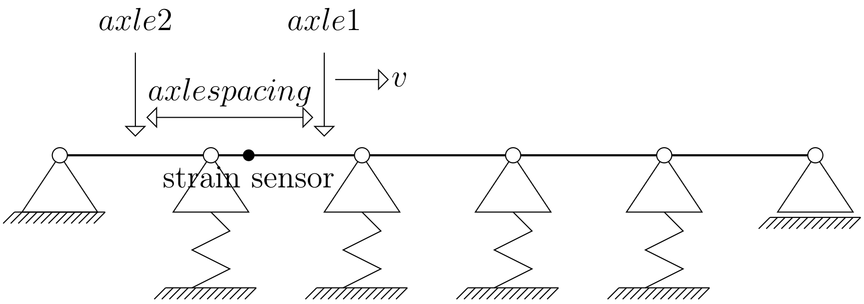


Figure 4: A more realistic beam bridge model

4.1.2 Finding the speed of the train

Two working methods of finding the speed of a passing train were developed:

- By identifying peaks in the strain history for two different sensors, representing the same axle. The distance between the two sensors and the time difference between the found peaks should theoretically give a good estimate of the trains velocity.
- Through doing cross correlation between two sensors strain history. This involves finding the phase difference, or lag, between the signals. The known distance between the strain gauges should then along with a constant, based on distance between sensors, give a reliable estimate of train velocity. INSERT PLOT OF CORRELATION AND SHOW MATHEMATICAL EQUATION DESCRIBING CROSS CORRELATION.

4.2 Finding influence lines

Describe how influence lines have been found from the given strain history from Lerelva Bridge. Keywords:

- Matrix method
- Optimization
- Speed

4.2.1 Matrix method

Describe the matrix method.

4.2.2 Optimization

Describe how optimization can be used to find optimal influence lines for the bridge.

4.3 System setup

To test the BWIM-program on actual data, we Gunnstein, Daniel set up a BWIM-system to gather strain data from actual train passings. The subject bridge were Lerelva-Bridge in Trondheim, figure 6, a typical Norwegian steel railway bridge. Three strain gauges, 3 mm 120 ohms from HBM, were placed by the support towards Trondheim on the first section of the longitudinal stringer, see figure 5b. The sensors were placed with 1 m spacing around the middle of the stringer section. These strain gauges were connected to a National Instruments compactDAQ with module NI 9235 which produced an continuous data flow to a standard laptop, see figure 5a. A Kipor generator was brought for power.

(a) System setup from data gathering at Lerelva

(b) Placement of strain gauges on stringer section

Figure 5: Instruments for aquiring strain data

Figure 6: Lerelva bridge with a train passing over

4.4 Testing

Keywords:

- Comparing calculated strain with measured strain

- Perform the same test with a influence line found through the matrix method

When performing BWIM with a influence line through the matrix method, the length of the strain signal will require a influence line of a certain length. The exact position where the train begins to influence the bridge is not known due to the special conditions of the Trondheim side support and the dynamic effects in the influence line. To use the found influence line as correctly as possible, it will be needed to place it in accordance with the provided strain signal.

4.4.1 Using calculated influence lines

To perform a standard BWIM calculation, the influence line needs to be aligned correctly with the strain signal, otherwise calculated Axle weights will be based on faulty calculations from solving the system

$A = I_m \backslash \varepsilon$ (NEEDS TO BE IN THEORY). The first peak of the strain signal, corresponding to the first axle of the train, should occur at the same location as the peak of the influence line which should be precisely at the strain-gauge/sensor location. Identifying the first peak of the strain signal is subject to noise which corrupts any reading of peaks in the raw strain signa. Therefore filtering of noise is needed to correctly identify the signals peaks. A trains axle spacings, as seen in B.1 which is the train type of the readings, may consist short spacings. If the axle spacing between two axles are short compared to the bridge, they both influence the signal simoultaneously and the peaks corresponding to the two axles thus lies very close to each other. The filtering can therefore not be to hard or soft, which may result in problems when trying to automate the procedure of identifying axles. To correctly align the strain signal and influence line, the matlab code used in this thesis first smooths the strain signal to a degree where the desired number of peaks are identifyable before using matlabs findpeaks (REFERENCE THIS) procedure to find the peak locations, like seen in figure 8.

The influence line is

(The noise level seem to vary according to sensor location.. Place in theory maybe!!)

5 Analysis

This chapter will describe how the BWIM system performs. What works? Why? How? etc. The main focus should perhaps be placed on identifying the pros and cons of the matrix method and optimization method.

Should include:

- Compare theoretical and calculated influence lines. Also include influence lines found through Abaqus.

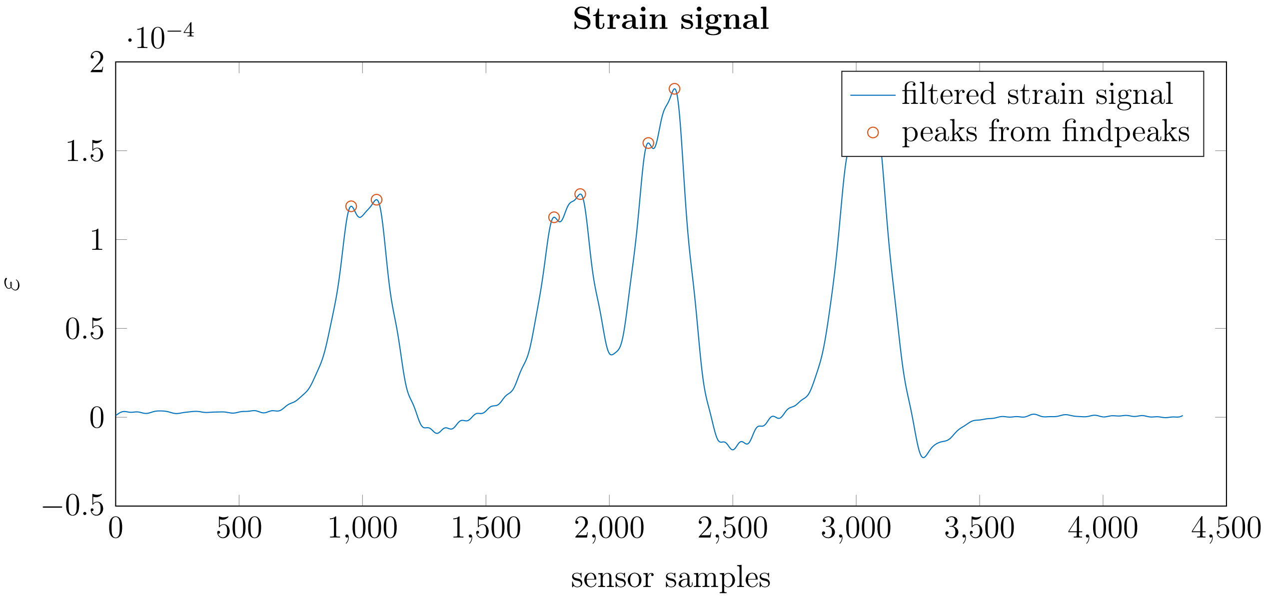


Figure 7: Axle peaks in strain signal

- Check how influence lines found through matrix method and optimization reproduces the strain history
- Test obtained influence line by running the bwim routine on the hitherto unused freight train. (Depends on getting info about the train). Also Do this test on the other trains.

5.1 Strain data

The following figure 9, contains raw strain data for 6 different trains passing the Lerelva bridge. Each subfigure contains data from three different strain sensors placed as described in System setup, see section:4.3. Three of the trains comes from the north side; train 3, train 5 and train 7, and three from the south side; train 4, 6 and 8. The strain signals all appear similar in form, except for train 7, figure9e, which is a freight train. The other 5 trains are all of the same type, a NSB 92 type passenger train B.1.

To account for the different directions of the trains, the strain data for the trains going towards Trondheim has been reversed (correct word ?). This is not necessary for finding influence lines, but makes it easier placing the found influence lines in the same coordinate system.

The strain data from the freight train, figure 9e, is not used for finding the bridge's influence line because the train data is unknown. Axle weights for this

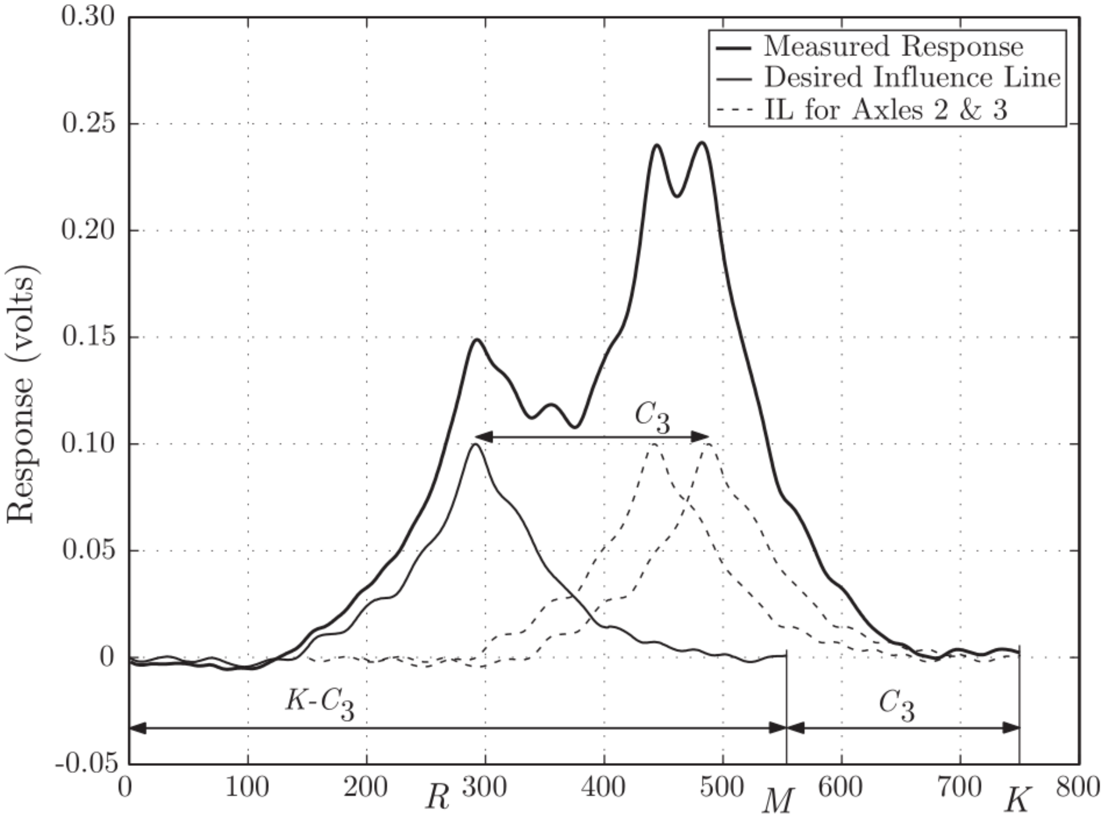
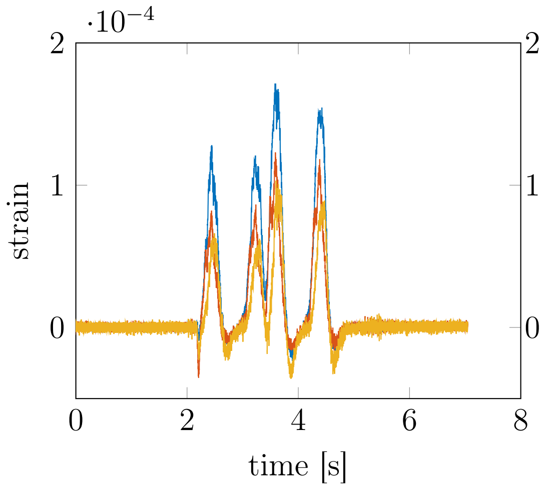
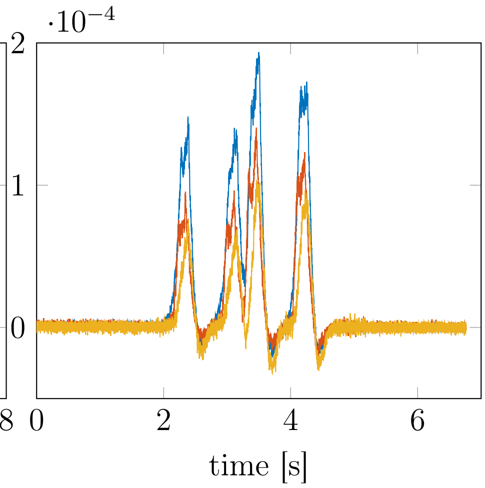


Figure 8: Axle peaks in strain signal

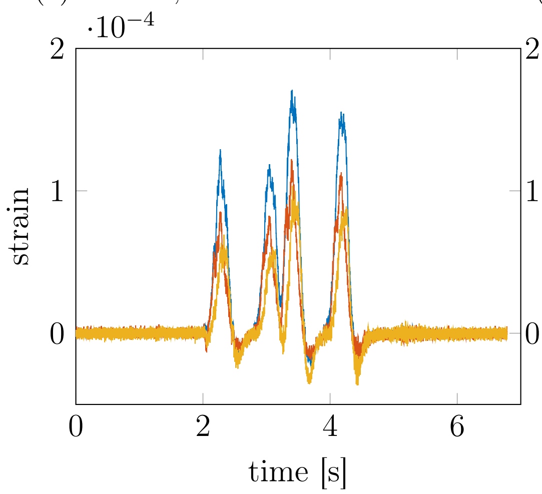
train was not found, and guesswork of this data would be difficult. The locomotive data, and possibly the axle spacings of the train, would be the only data possible to find. Therefore this data will only be used for testing of influence lines.



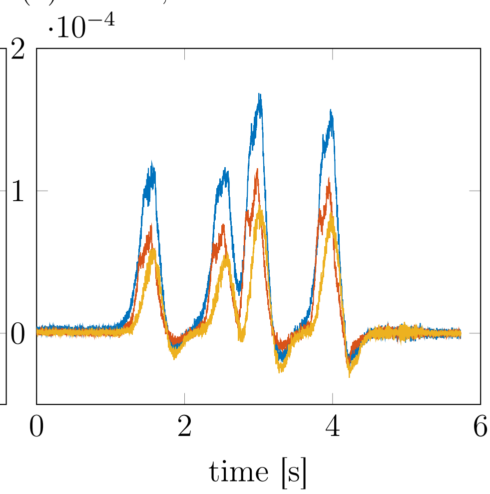
(a) Train 3, towards Heimdal



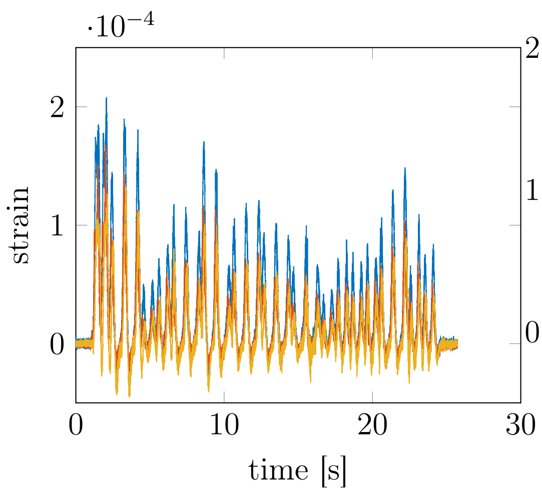
(b) Train 4, towards Trondheim



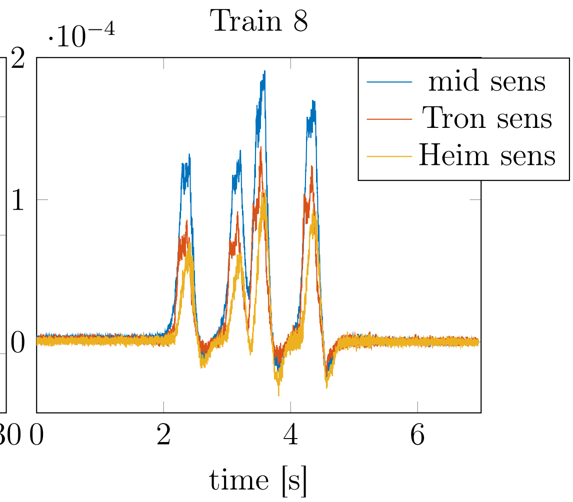
(c) Train 5, towards Heimdal



(d) Train 6, towards Trondheim



(e) Freight train, towards Heimdal



(f) Train 8, towards Trondheim

Figure 9: Strain data from Leirelva bridge

5.2 Optimized influence lines

Perform the same procedures as for the matrix method

5.3 Differences between the methods

Compare the optimized influence lines and the matrix method influence lines. This should be done in a thorough manner.

5.4 Problems

- Big problem with identifying exactly when train enters and leaves the bridge. This results in guesswork when placing influence line in a coordinate system. Where does the bridge begin and end in the influence line.. The only definite certainty seems to be placing the index of the maximum magnitude of the influence line in the correct position according to the measuring sensor's location.

- This could be problematic when using the found influence lines

- These problems have been reduced, now the biggest problem is placing the peak of the influence line as well as possible. Possibly performing a smoothing and then finding position of peak could give a better estimate of sensorloc at influence line.. currently the max value of influence line is placed at sensorloc.

5.5 The matrix method

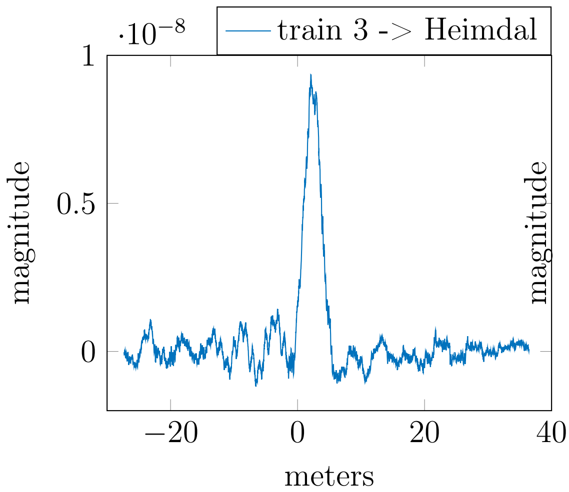
The matrix method creates an influence line for a specific strain history given a known train with known axle weights and velocity. Thus if the strain signal were recreated given with given parameters, the signal would be a almost exact replica of the measured strain signal, where the differences should originate from sensor noise. The found influence line would however be for this specific train and the passing's dynamic effects on the bridge, which is likely to vary from train to train. Therefore an averaging of a sufficient number of calculated influence lines should reduce or eliminate the dynamic effects from the influence line.

The analysis of the matrix method is based on 4 different train passings, and 3 sensor readings on each passing. The trains in these measurements is of the same type (not entirely shure!!) but the exact weight is not known. The weight of each axle were approximated by distributing carriage and locomotive gross weight. Passengers in the passing trains were not accounted for, and may lead to some deviation from ideal results.

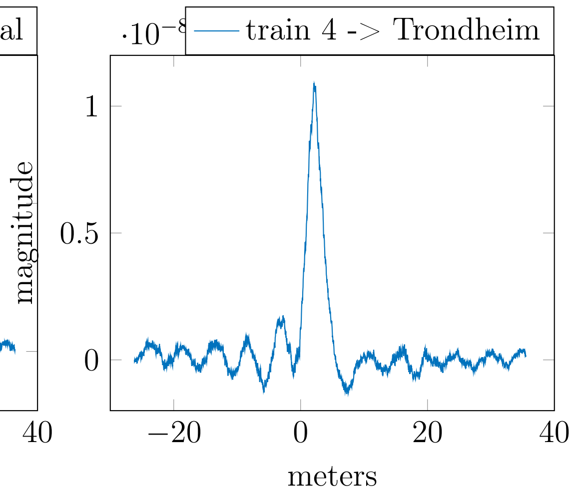
To include effects from the train approach to the bridge, additional samples have been included from the strain signal before and after the first and last peak found in the signal. This will recreate the strain signal to a more complete degree (needs to be shown in a figure), but the found influence line usually displays more dynamic effects which is unwanted properties in a static influence line.

TODO:

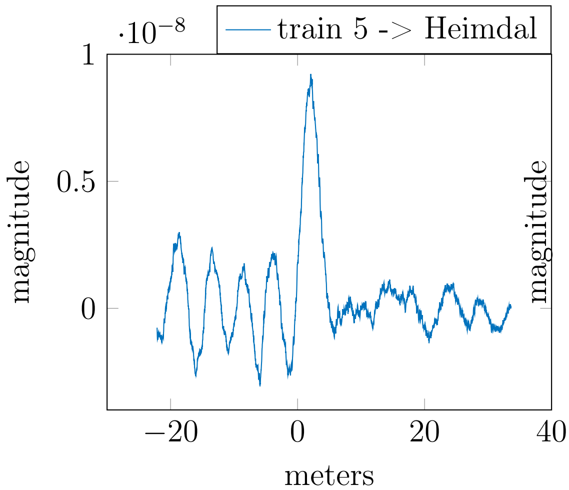
- soutShow the found influence lines for some sensors
- discuss the plots
- reproduce strain signal, and compare with measured signal
- soutshow averaged influence line, and perform the same tests
- show interpolation of this averaged influence line
- perform the same test with this interpolated influence line
- the alternative should also be done, interpolate each found influence line and average them, then reproduce the strain signal, and find difference through comparison.



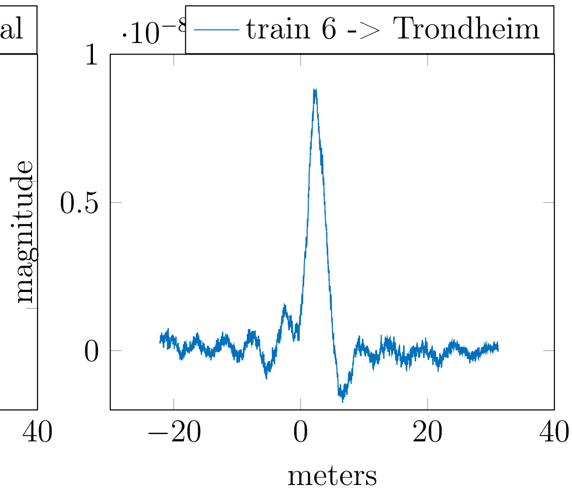
(a) Influence line train 3



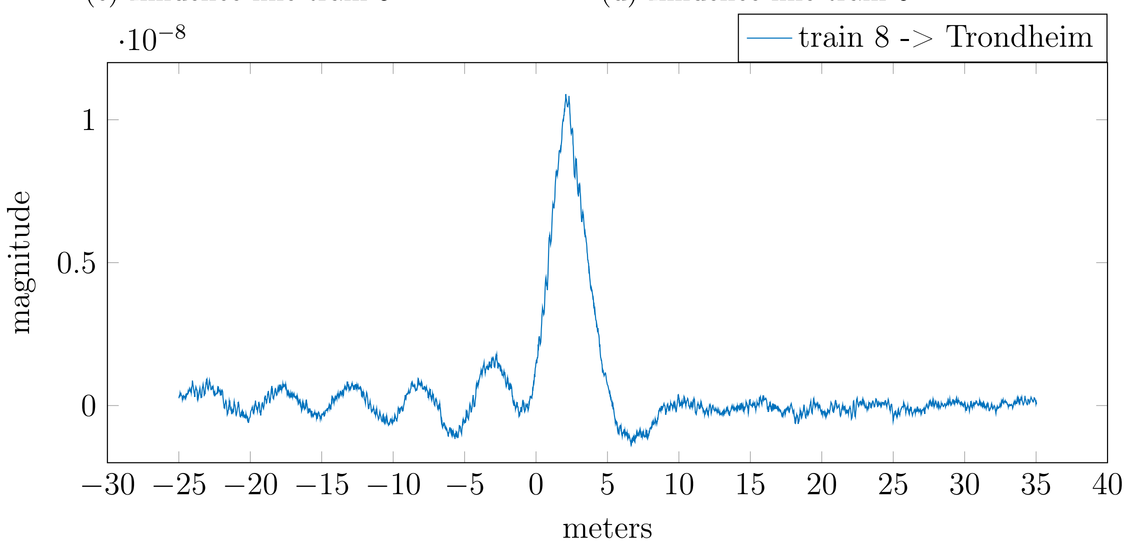
(b) Influence line train 4



(c) Influence line train 5



(d) Influence line train 6



(e) Influence line train 8

Figure 10: Influence lines found through the matrix method, for the middle sensor

As plainly seen in figure 10 there is big differences between the found influence lines. The trains are all of the same type meaning that the magnitudes of the influence lines, which should be the mostly dependent on axle weights, ought to be similar for all train passings. When the plots are laid on top of each other, as in figure 14, it is clearly visible that there is some variation in peak magnitude. The passings max magnitudes appears to be very similar for trains going in the same direction. The trains coming from Heimdal towards Trondheim appears to create influence lines of a slightly higher magnitude than for trains going in the oposite direction.

5.5.1 Accuracy of the matrix method through recreating the strain signal

One way of examining the accuracy of the matrix method is to recreate the strain signals by using the calculated influence lines. The following three subfigures show recreated signals for a single train passage, but for different sensor locations.

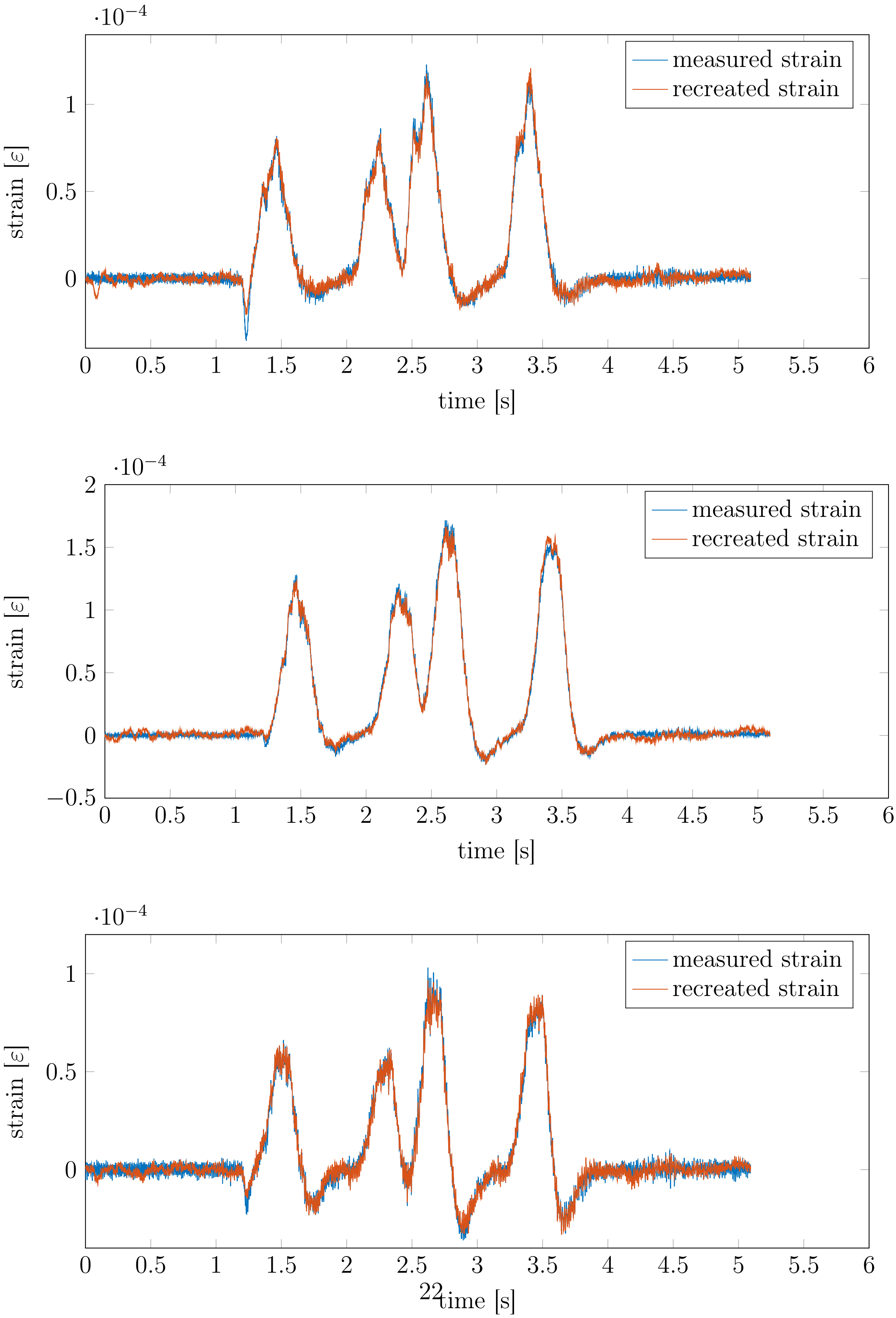


Figure 11: Recreated strain signals for train 3

Error table			
	Trondheim sensor	middle sensor	Heimdal sensor
train 3	$Error = 3.8684 \cdot 10^{-8}$	$Error = 3.9936 \cdot 10^{-8}$	$Error = 3.0987 \cdot 10^{-8}$
train 4	$Error = 3.7437 \cdot 10^{-8}$	$Error = 2.6794 \cdot 10^{-8}$	$Error = 2.4965 \cdot 10^{-8}$
train 5	$Error = 4.5112 \cdot 10^{-7}$	$Error = 2.3935 \cdot 10^{-7}$	$Error = 1.9847 \cdot 10^{-7}$
train 6	$Error = 5.3555 \cdot 10^{-8}$	$Error = 2.8783 \cdot 10^{-8}$	$Error = 2.4336 \cdot 10^{-8}$
train 8	$Error = 3.6865 \cdot 10^{-8}$	$Error = 2.3341 \cdot 10^{-8}$	$Error = 2.6944 \cdot 10^{-8}$
average	$Error = 1.2353 \cdot 10^{-7}$	$Error = 7.1641 \cdot 10^{-8}$	$Error = 6.1141 \cdot 10^{-8}$

Table 1: Errors of the recreated strain signals found in 11, rounded to four decimals

Figure **??** shows a strain signal from the sensor closest to Trondheim along with a signal recreated using the found influence line for that sensor. To identify and compare errors the following equation 11, performing least square error, will be used.

$$Error = \sum (\varepsilon_{meas} - \varepsilon_{calc})^2 \tag{11}$$

The recreated strain signals, see figure 11, illustrates the accuracy of the matrix method. However this way of using the found influence lines will.

Train 5 is clearly distinctive, in regards of how it oscillates in plot 10c and how it recreates the strain with error as in table 1. There are several possible causes for these deviating results, among them wrongly determined velocity of the train and that the trains speed amplifies dynamic effects in the bridge and sensor.

Error table for 600 samples before and after, for smoothed and unsmoothed signal. Also excluding train 5 which is found to show large dynamic effects. Filtering removes frequencies above 10 Hz.

Error table, filtered signals			
	Trondheim sensor	middle sensor	Heimdal sensor
train 3	$Error = 9.0579 \cdot 10^{-8}$	$Error = 8.8553 \cdot 10^{-8}$	$Error = 8.2682 \cdot 10^{-8}$
train 4	$Error = 5.8366 \cdot 10^{-8}$	$Error = 9.8604 \cdot 10^{-8}$	$Error = 6.0953 \cdot 10^{-8}$
train 6	$Error = 4.9018 \cdot 10^{-8}$	$Error = 9.2035 \cdot 10^{-8}$	$Error = 4.5365 \cdot 10^{-8}$
train 8	$Error = 5.4430 \cdot 10^{-8}$	$Error = 9.5485 \cdot 10^{-8}$	$Error = 6.5290 \cdot 10^{-8}$
average	$Error = 6.3098 \cdot 10^{-8}$	$Error = 9.3669 \cdot 10^{-8}$	$Error = 6.357 \cdot 10^{-8}8$

Table 2: Errors of the recreated strain signals with original signal filtered for noise, rounded to four decimals

Table 3: Error table w/o filtering

Error table, w/o filtering			
	Trondheim sensor	middle sensor	Heimdal sensor
train 3	$Error = 5.9214 \cdot 10^{-8}$	$Error = 6.3572 \cdot 10^{-8}$	$Error = 3.9315 \cdot 10^{-8}$
train 4	$Error = 3.3116 \cdot 10^{-8}$	$Error = 7.1066 \cdot 10^{-8}$	$Error = 3.1627 \cdot 10^{-8}$
train 6	$Error = 3.3947 \cdot 10^{-8}$	$Error = 6.9690 \cdot 10^{-8}$	$Error = 2.9709 \cdot 10^{-8}$
train 8	$Error = 2.8439 \cdot 10^{-8}$	$Error = 6.6137 \cdot 10^{-8}$	$Error = 3.6453 \cdot 10^{-8}$
average	$Error = 3.8679 \cdot 10^{-8}$	$Error = 6.7616 \cdot 10^{-8}$	$Error = 3.4276 \cdot 10^{-8}$

Should be a caption

The differences between the unfiltered and filtered errors, tables 2 and 3 respectively, are clear but not unexpected. They show that the filtering does not distort the error to an amount which destroys the accuracy of the influence line. To really compare the methods of filtering however the found influence lines should be used to calculate axle weights. Averaging of the influence lines gives the following plots.

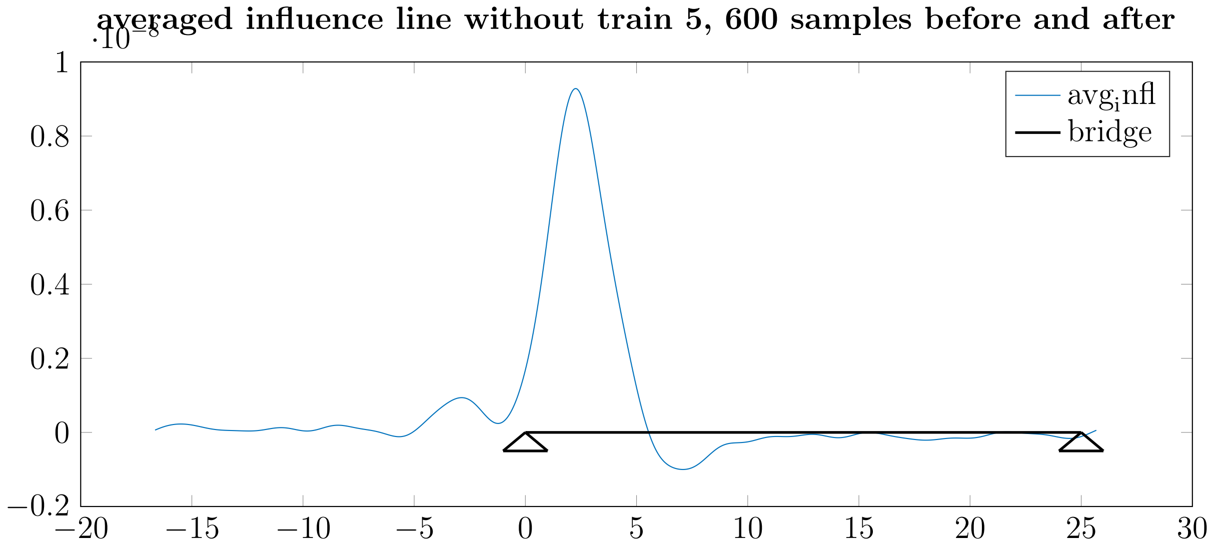


Figure 12: Influence line, filtered after averaging

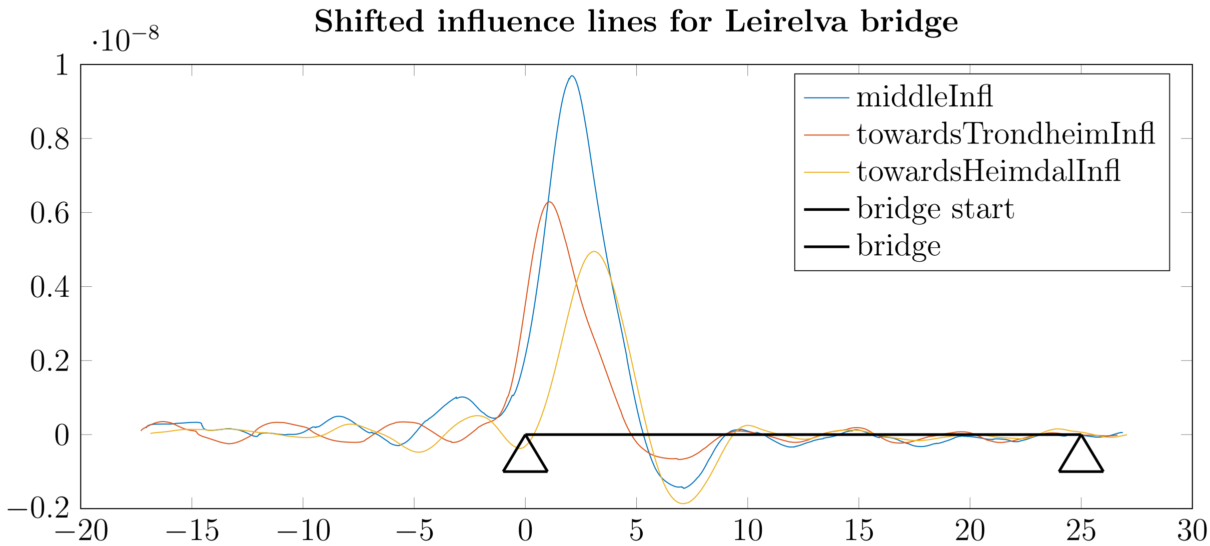


Figure 13: Influence line, filtered strain signals

5.5.2 Dynamic effects

The dynamic effects can clearly be seen in the plots for the various train passings. They appear as oscillations in the plots, and are more visible in the low magnitude areas of the influence line. These oscillations vary from train to train making it clear that the dynamic effects depends on the train. The varying influencing factors may be train speed and weight. In the source code producing these influence lines an assumption of train weight has been made, which makes all train axles equal in weight. What is interesting is the effects of an approaching train, which clearly induces oscillations in the bridge even though the train is as far as 40 meters away from the beginning of the bridge. The differences between the dynamic effects for the train passings may relate to velocity, axle weights and train acceleration (there may be more causes).

These dynamic effects are unwanted in the static influence line. In theory, averaging enough influence lines should reduce these effects enough to get usable data. This thesis does not contain enough train passings to achieve this. Also as mentioned before, one of the trains have amplified dynamic effects which throw off the results somewhat when performing averaging. Therefore exluding the results from train 5 as in would be reasonable. Figure 16 shows the average of the different influence lines where train 5 has been excluded. This plot still contain dynamic effects, which will need to be removed, but the amplitude of the oscillations have been visibly reduced. Shortening the number of samples in the case without train 5, reduces the dynamic effects furter, and a filtering of higher frequencies gives amore usable influence line as seen in 17. A general formula for identifying influence lines with too much oscillation should be developed. One way could be to use table 1 and exlude the trains which dominates error, or that differs most from the other trains.

The support towards Trondheim is of a special nature, it is connected to a very little bridge spanning perhaps 2 meters which cars may pass under. This may affect the trains entry and cause dynamic effects. It also provides a problem when deciding what should be part of the final influence line, what influences the sensor? One way to do it would be to simply cut the influence line at the samples corresponding to the bridge, however that does not seem likely to be a very good solution. Another way would be to smooth the influence line to the point where the entry part becomes itegrated with the the major influence line peak.

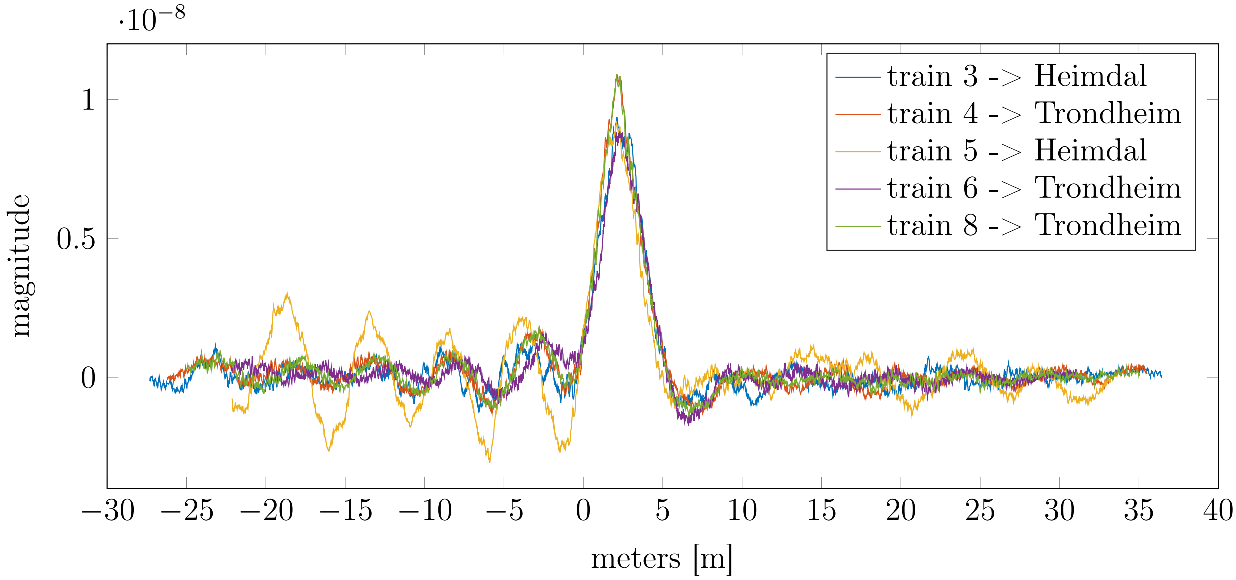


Figure 14: Influence lines from figure:10 on top of each other

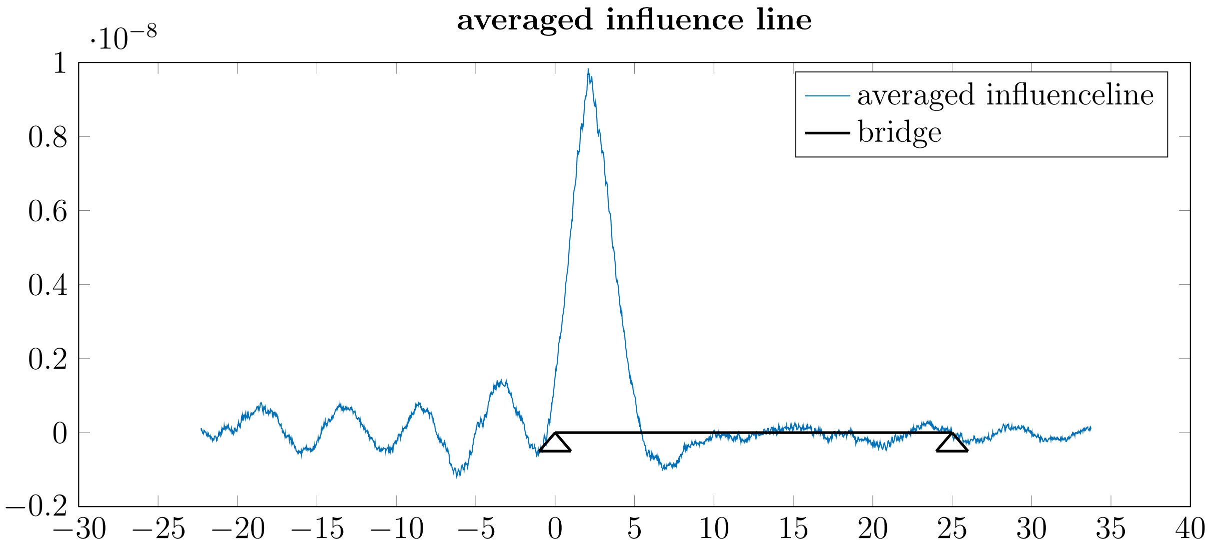


Figure 15: Averaged of the 5 trains

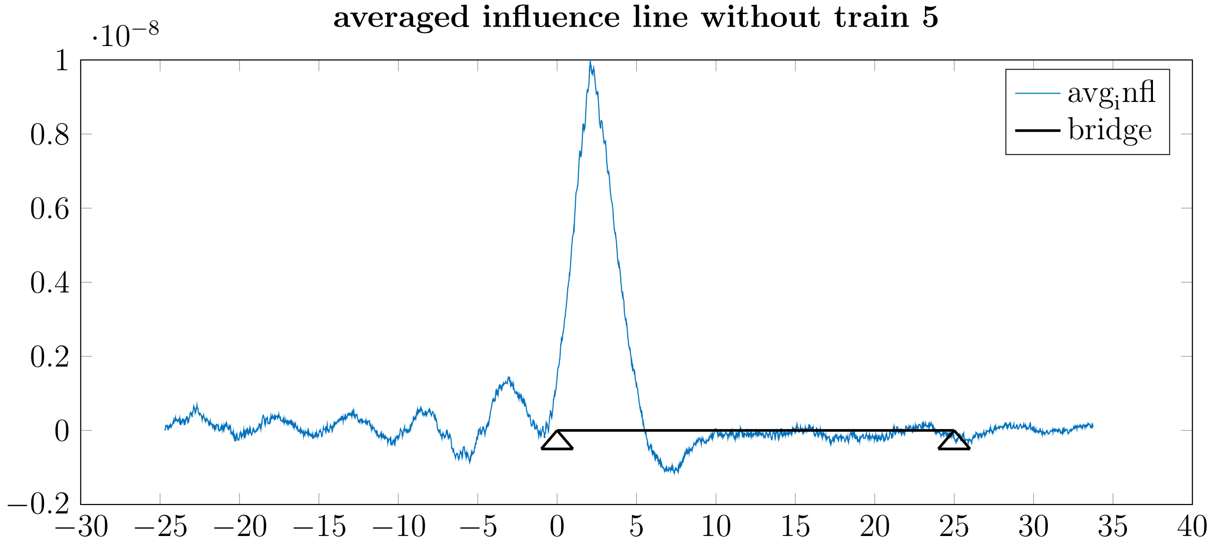


Figure 16: Averaged influence line without train 5

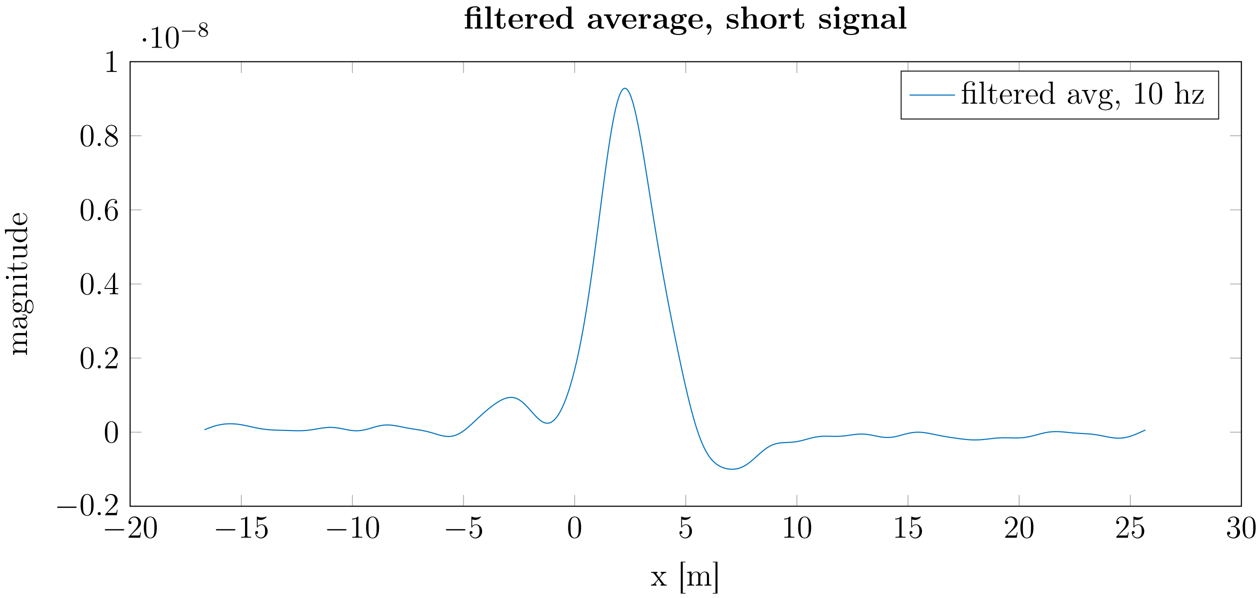


Figure 17: Shorter averaged influence line without train 5

A possible way to place the found influence line is shown in figure 15, which places the influence line in the assumed position on the bridge. The maximum magnitude of the influence line should be found at the sensor location, thusly the averege influence line has been placed in the corrdinate system of the bridge accordingly. There is however the problem of noise, which makes identifying the actual max peak difficult.

Filtering the signals so that a singular smooth maximum peak can be identified. This could distort the actual signal, but will be an interesting approach.

5.5.3 Calculate the axle weights

The axle weights used to calculate the influence lines are as in.

Axle	1	2	3	4	5	6	7	8
Axle weight [kg]	9500	9500	9500	9500	14575	14575	14575	14575

Axle	1	2	3	4	5	6	7	8
Train 3: axle weight [kg]	9500	9500	9500	9500	14575	14575	14575	14575
Train 4: axle weight [kg]	9500	9500	9500	9500	14575	14575	14575	14575
Train 6: axle weight [kg]	9500	9500	9500	9500	14575	14575	14575	14575
Train 8: axle weight [kg]	9500	9500	9500	9500	14575	14575	14575	14575

6 Conclusion and summary

References

[1] John Doe. *The Book without Title*. Dummy Publisher, 2100.

[2] A. Liljencrantz, R. Karoumi, and P. Olofsson. "Implementing bridge weigh-in-motion for railway traffic". English. In: *Computers and Structures* 85.1-2 (2007), pp. 80–88. URL: www.scopus.com.

[3] MATLAB. *Practical Introduction to Frequency-Domain Analysis*. URL: http://se.mathworks.com/help/signal/examples/practical-introduction-to-frequency-domain-analysis.html (visited on 05/20/2016).

[4] E. O'Brien, B. Jacob, and COST 323. "Second European conference on weigh-in-motion of road vehicles : Lisbon, 14th - 16th September, 1998". In: (1988), pp. 139, 152.

[5] Michael Quilligan. "Bridge Weigh-in Motion : Development of a 2-D multi-vehicle algorithm". NR 20140805. PhD thesis. KTH, Civil and Architectural Engineering, 2003, pp. viii, 144.

[6] J. Radatz and Institute of Electrical Electronics Engineers Standards Coordinating Committee 10. *The IEEE standard dictionary of electrical and electronics terms (6th ed., Vol. 100-1996, Institute of Electrical and Electronics Engineers). New York: Institute of Electrical and Electronics Engineers.* 1996.

A Dynamics

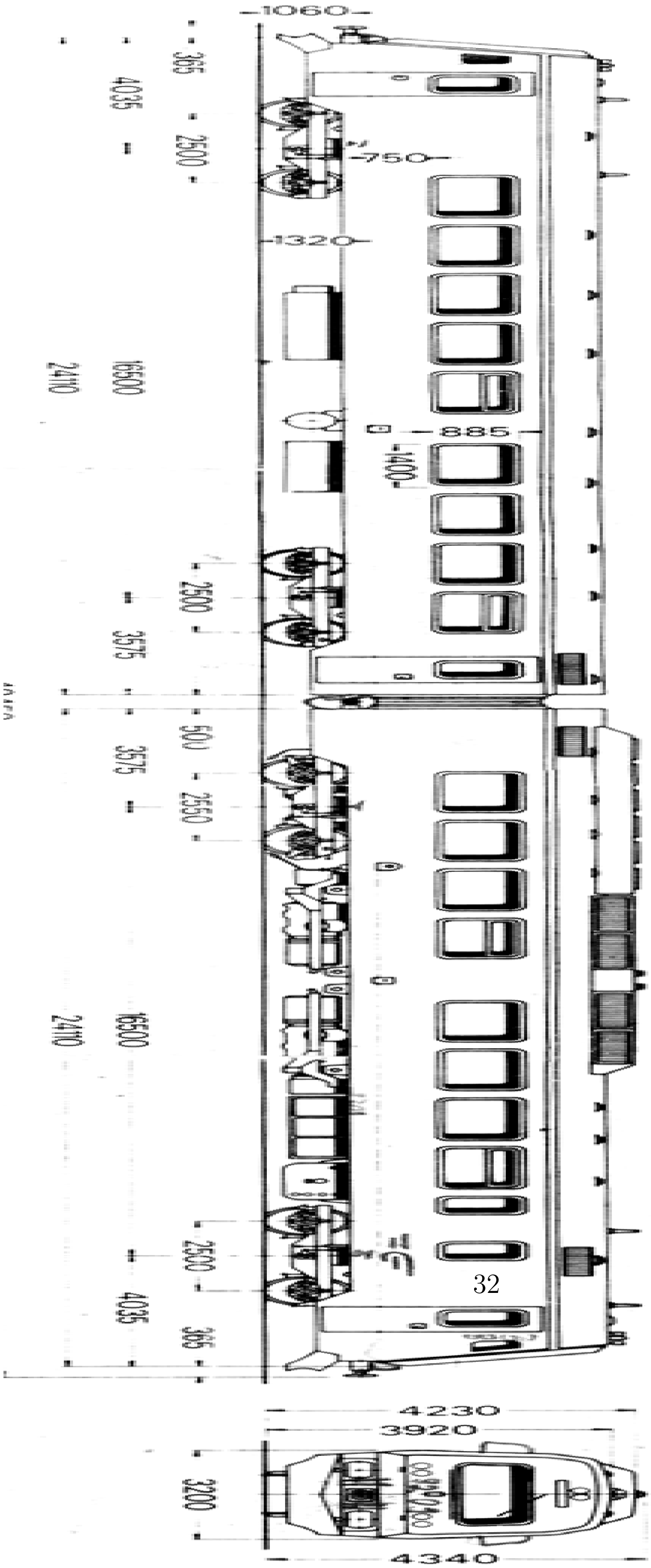
A train traversing a railway bridge creates actions in longitudinal, lateral, and vertical directions. Braking and traction from a passing train causes longitudinal forces Rocking, or rotations around an axis parallel to the longitudinal axis of the bridge, and vertical dynamic forces are created by structure-track-vehicle conditions and interactions.

A.1 Rocking and vertical dynamic forces

Lateral rocking of moving vehicles provide amplification of vertical wheel loads. This amplification increases the stresses in the members supporting the track. Superstructure-vehicle interaction creates a vertical dynamic amplification of moving loads, which will result in vibrations causing additional stresses in members supporting the track. The unloaded simply supported beam frequency $\omega_1 = \frac{\pi^2}{L^2}\sqrt{\frac{EI}{m}}$, provides a basic indicator of superstructure vertical dynamic response.

B Trains

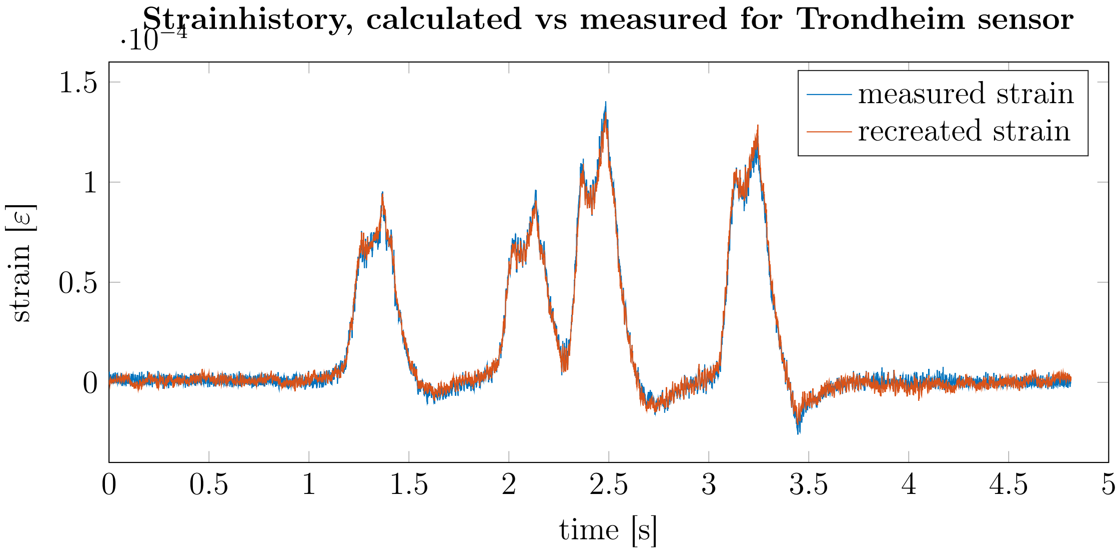
B.1 NSB92



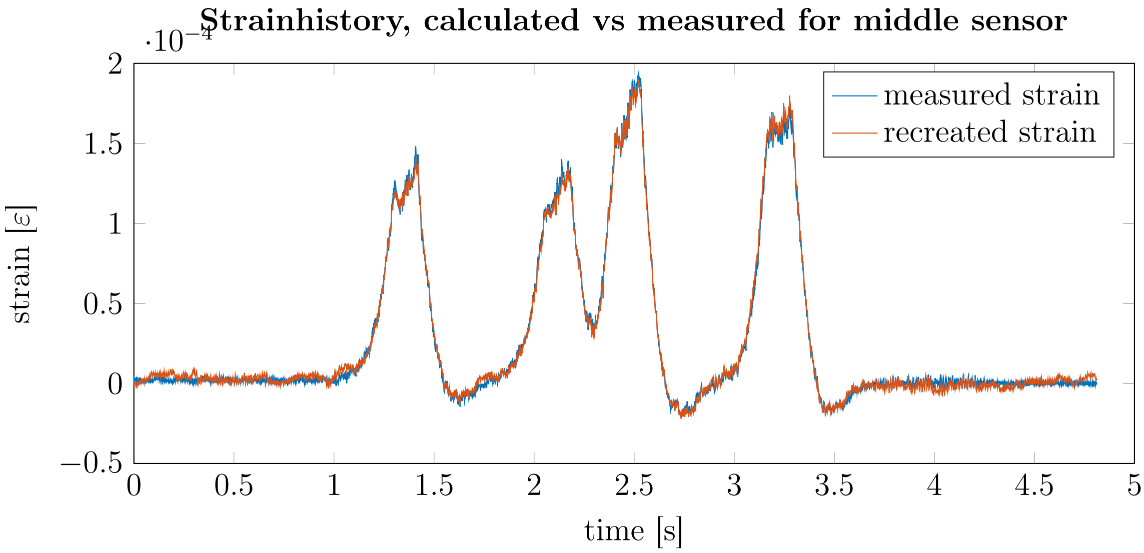
B.2 Freight train

C Figures

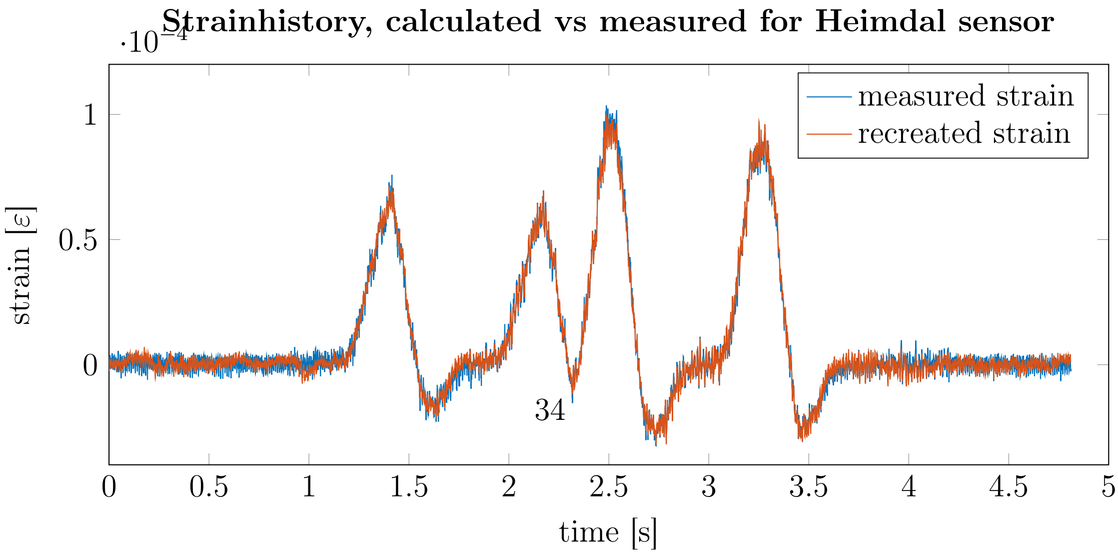
C.1 Recreated strain signals



(a) Recreated strain, Trondheim sensor, train4

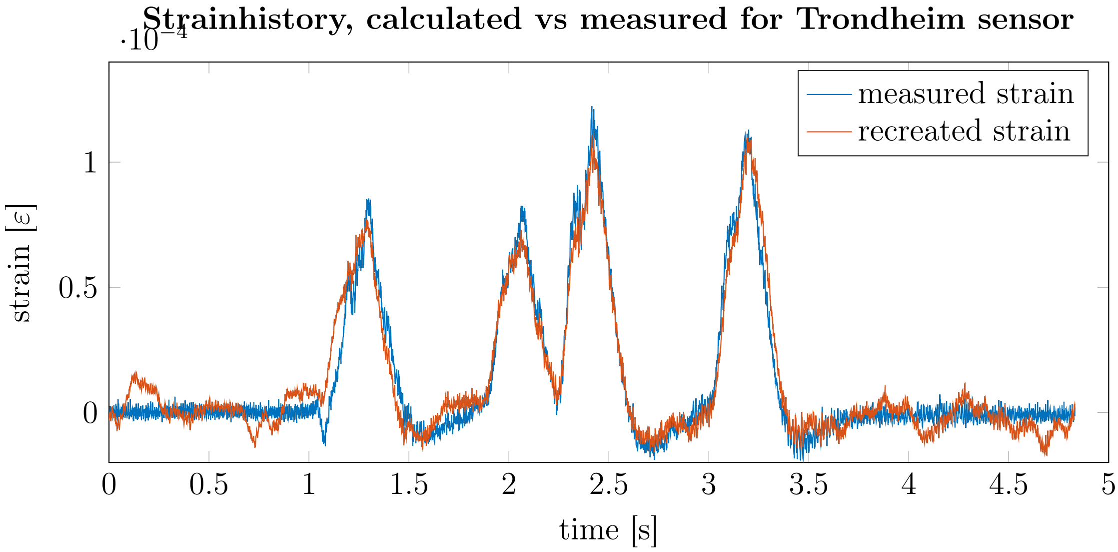


(b) Recreated strain, middle sensor, train4

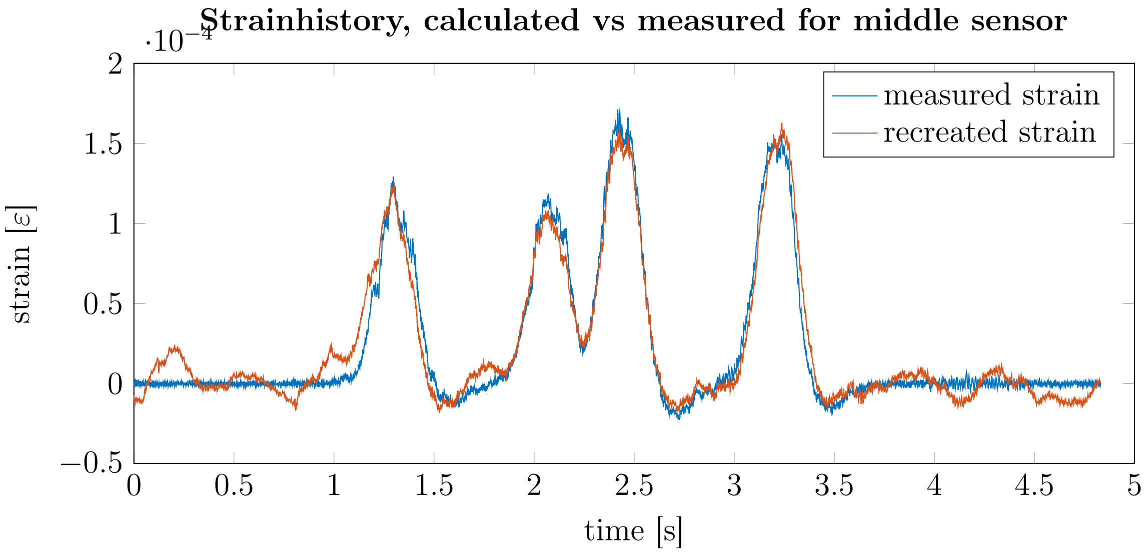


(c) Recreated strain, Heimdal sensor, train4

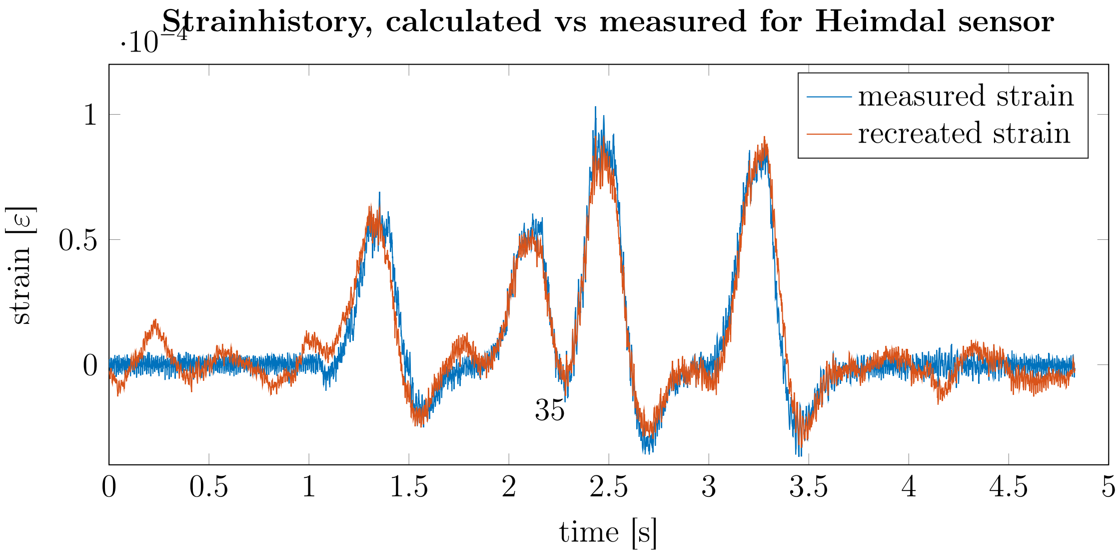
Figure 18: Recreated strain signals for train 4



(a) Recreated strain, Trondheim sensor, train5



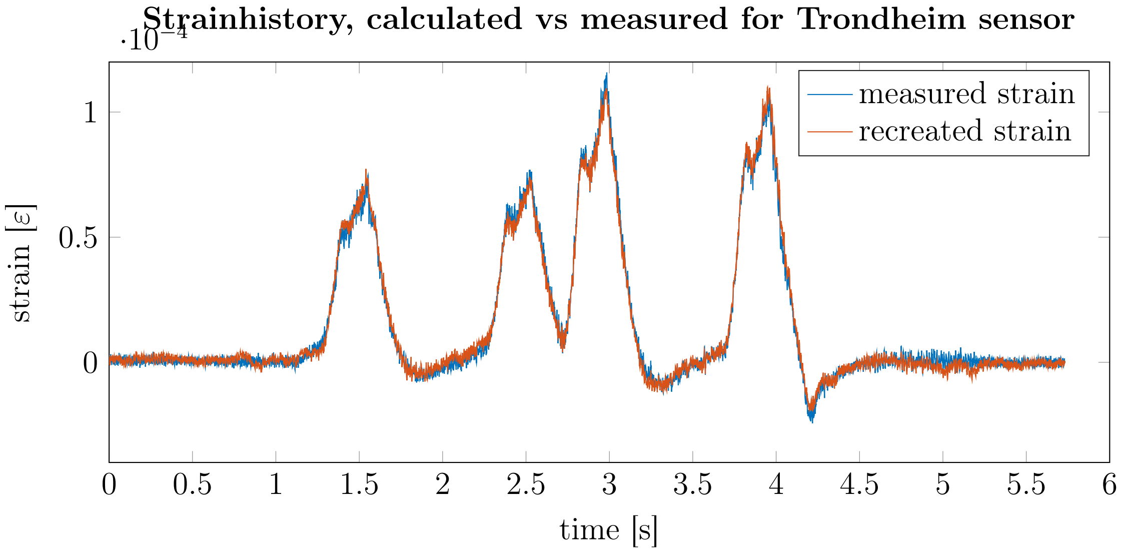
(b) Recreated strain, middle sensor, train5



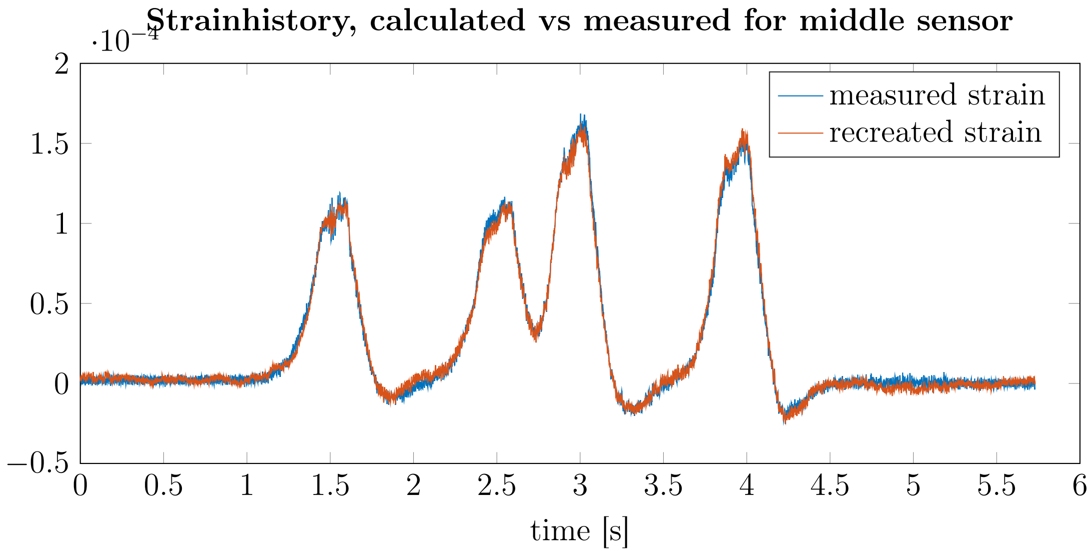
(c) Recreated strain, Heimdal sensor, train5

Figure 19: Recreated strain signals for train 5

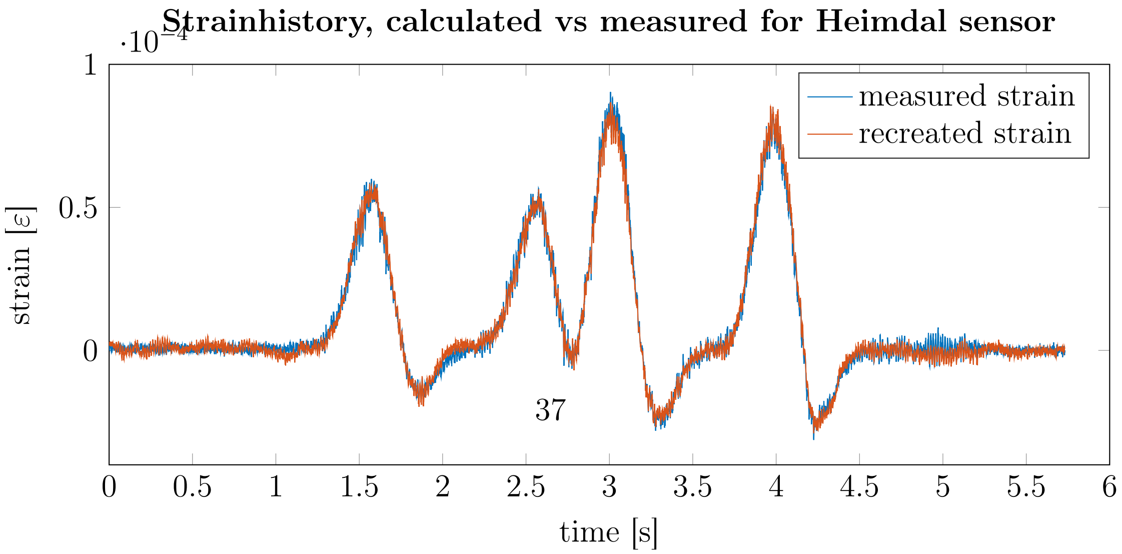
C.2 Influence lines all sensors



(a) Recreated strain, Trondheim sensor, train6

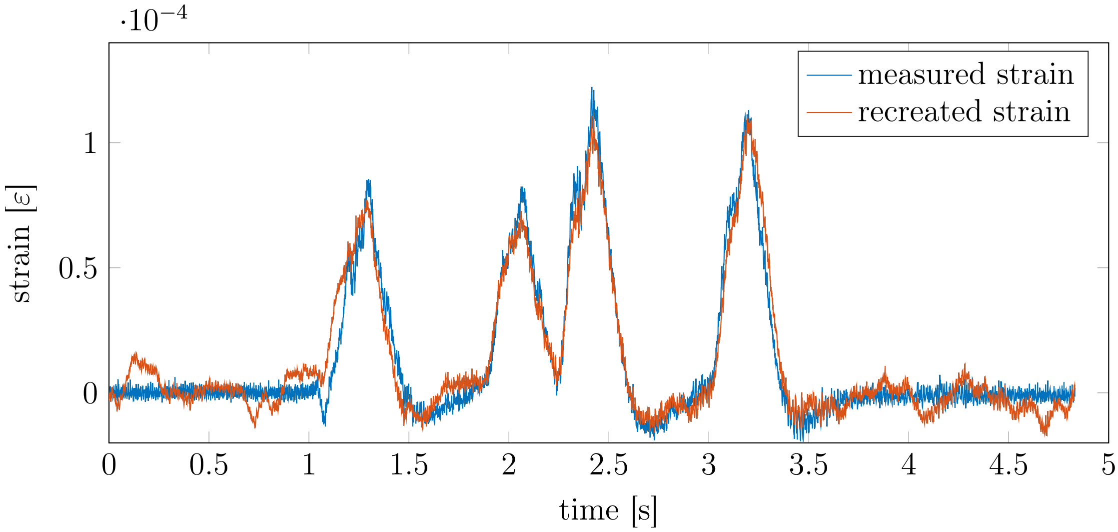


(b) Recreated strain, middle sensor, train6

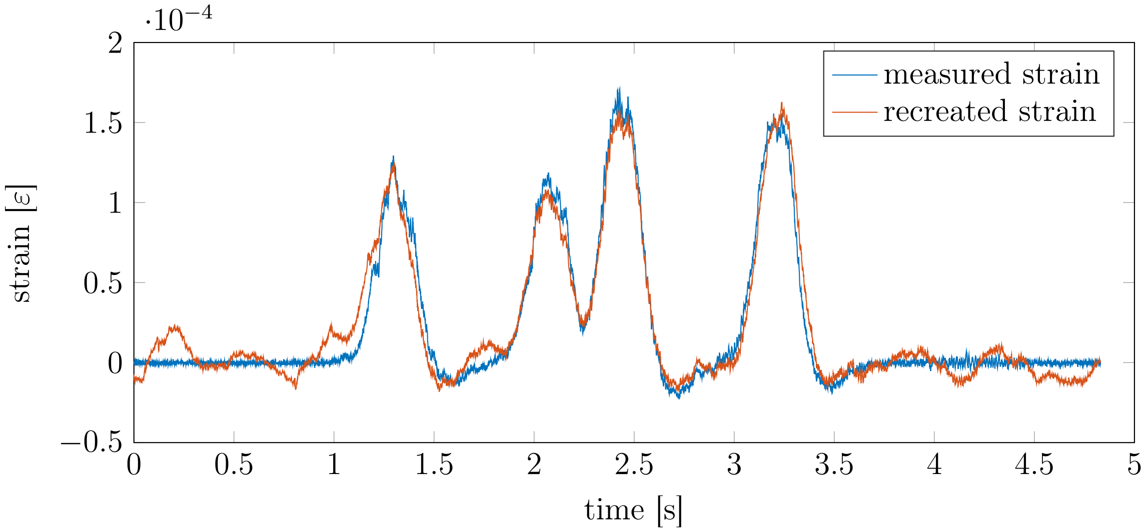


(c) Recreated strain, Heimdal sensor, train6

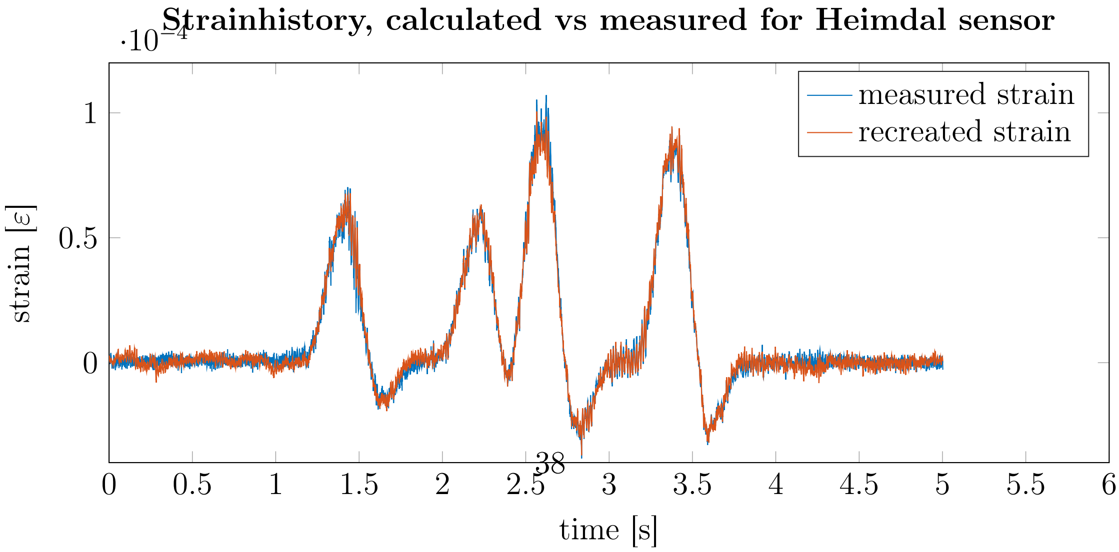
Figure 20: Recreated strain signals for train 6



(a) Recreated strain, Trondheim sensor, train8

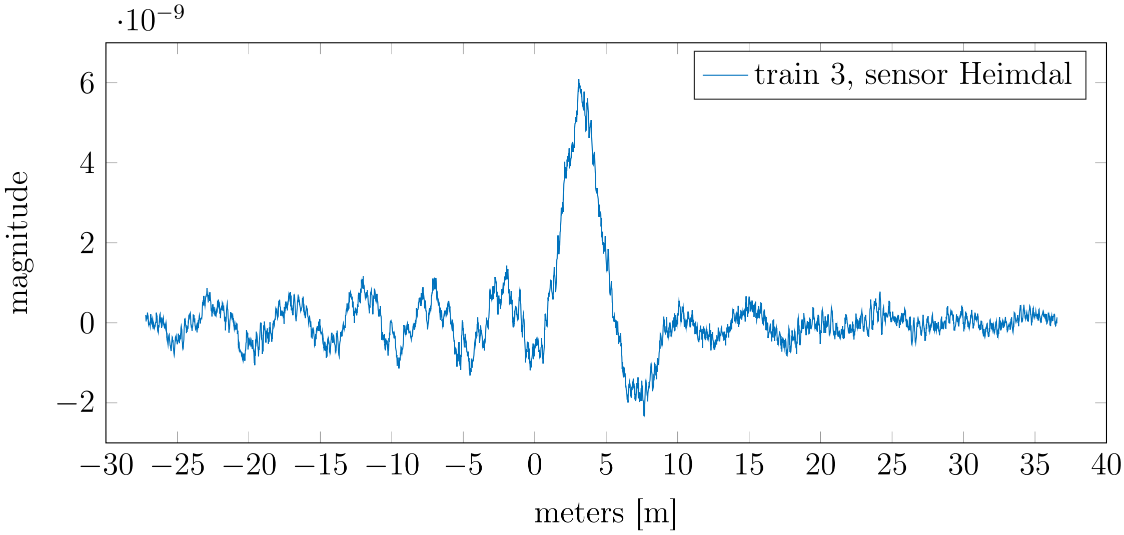


(b) Recreated strain, middle sensor, train8

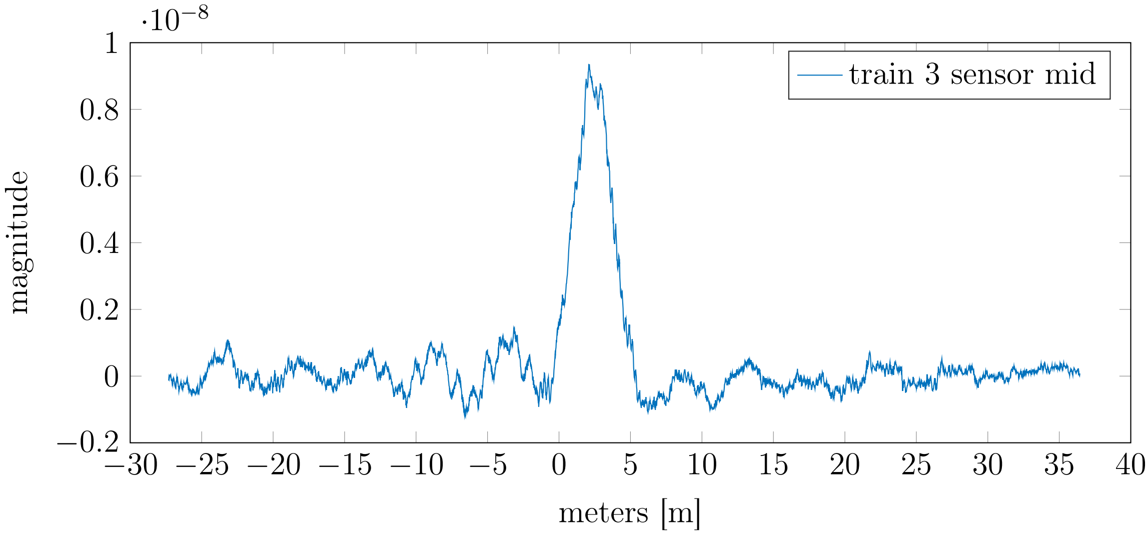


(c) Recreated strain, Heimdal sensor, train8

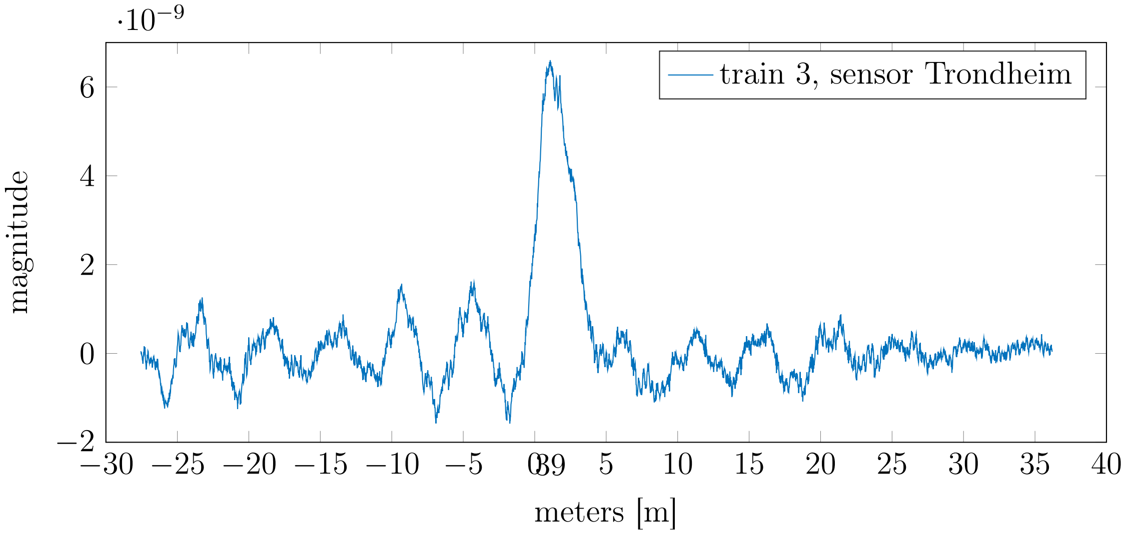
Figure 21: Recreated strain signals for train 8



(a) Influence line for sensor towards Heimdal, train 3

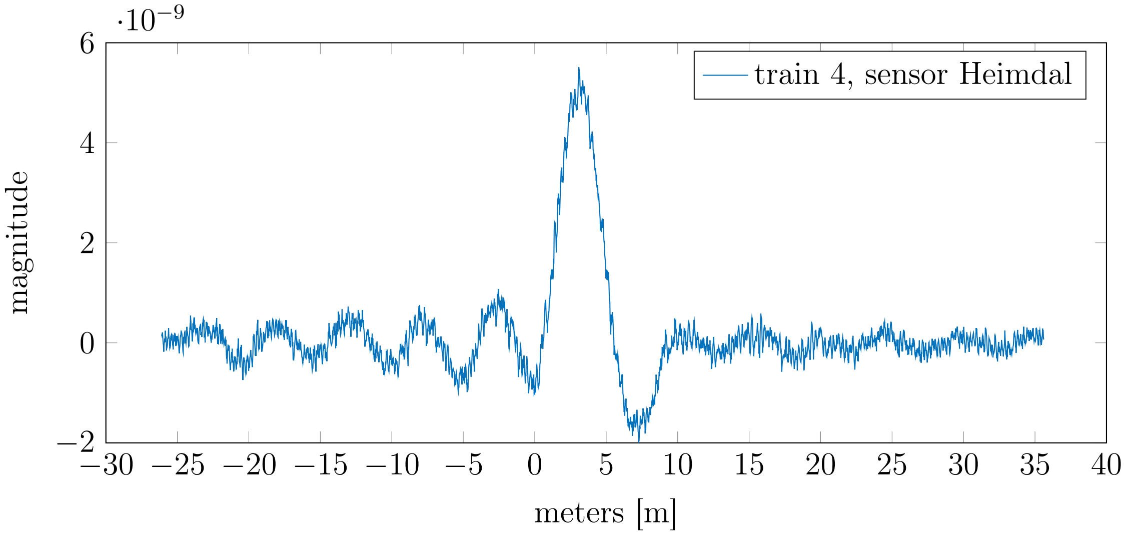


(b) Influence line for middle sensor, train 3

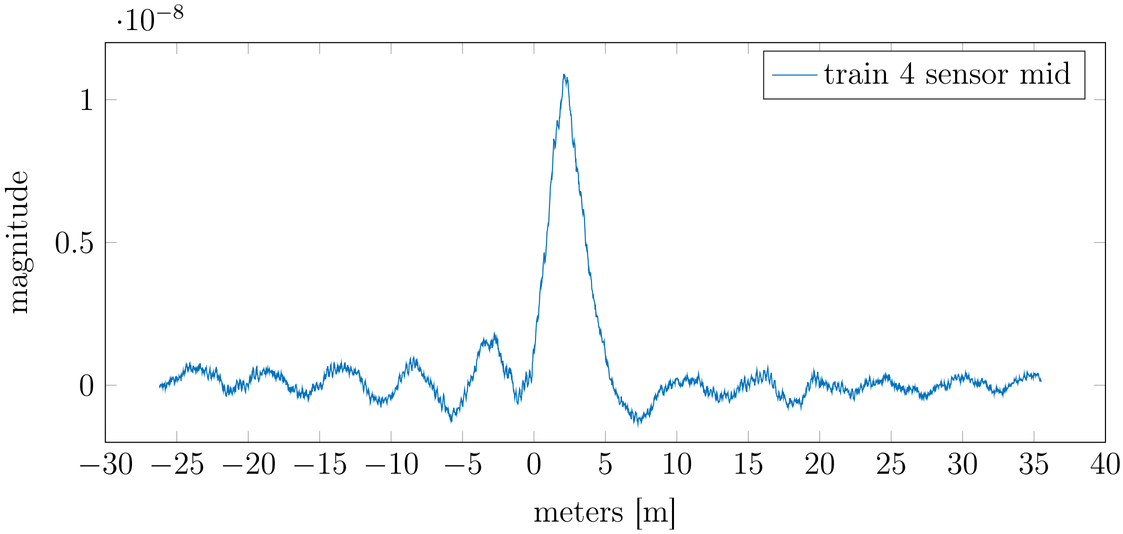


(c) Influence line for sensor closest Trondheim, train 3

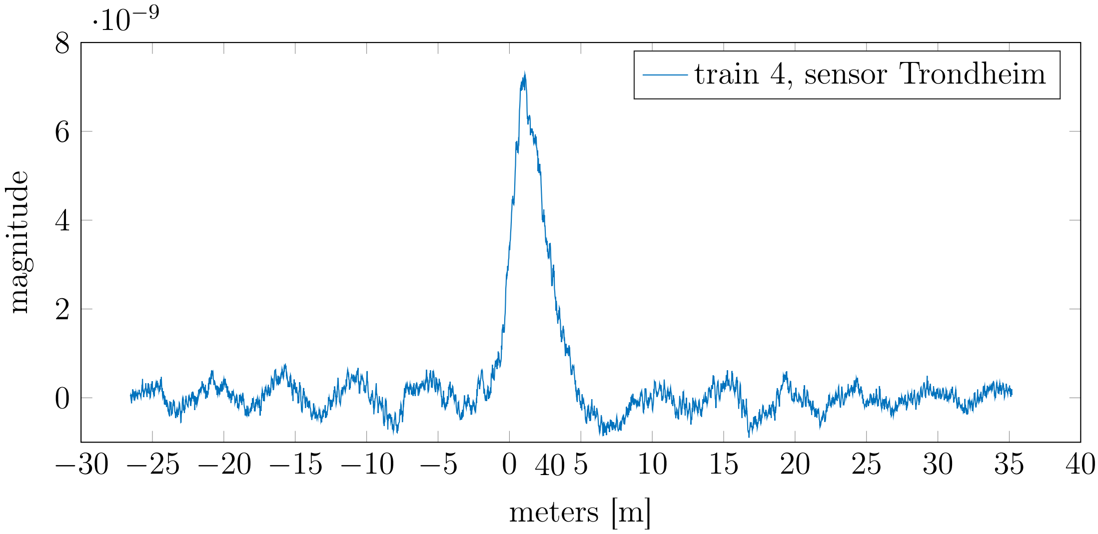
Figure 22: Influence lines train 3



(a) Influence line for sensor towards Heimdal, train 4

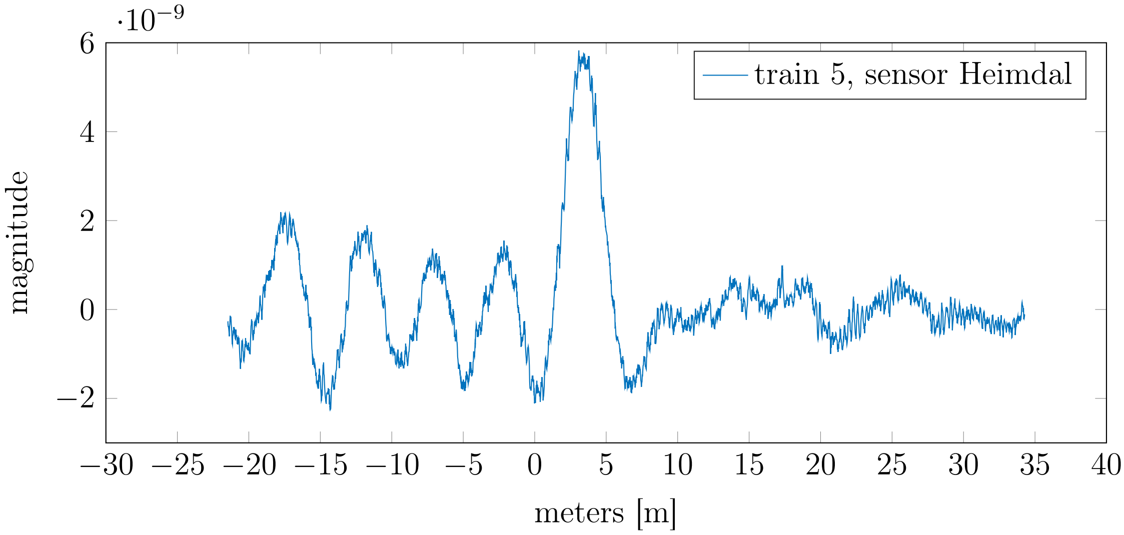


(b) Influence line for middle sensor, train 4

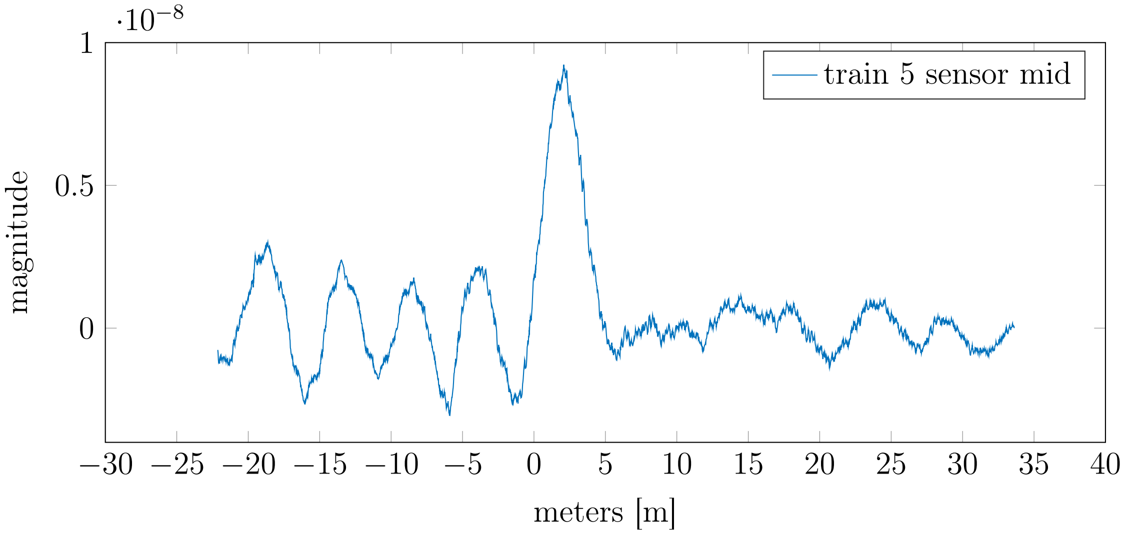


(c) Influence line for sensor closest Trondheim, train 4

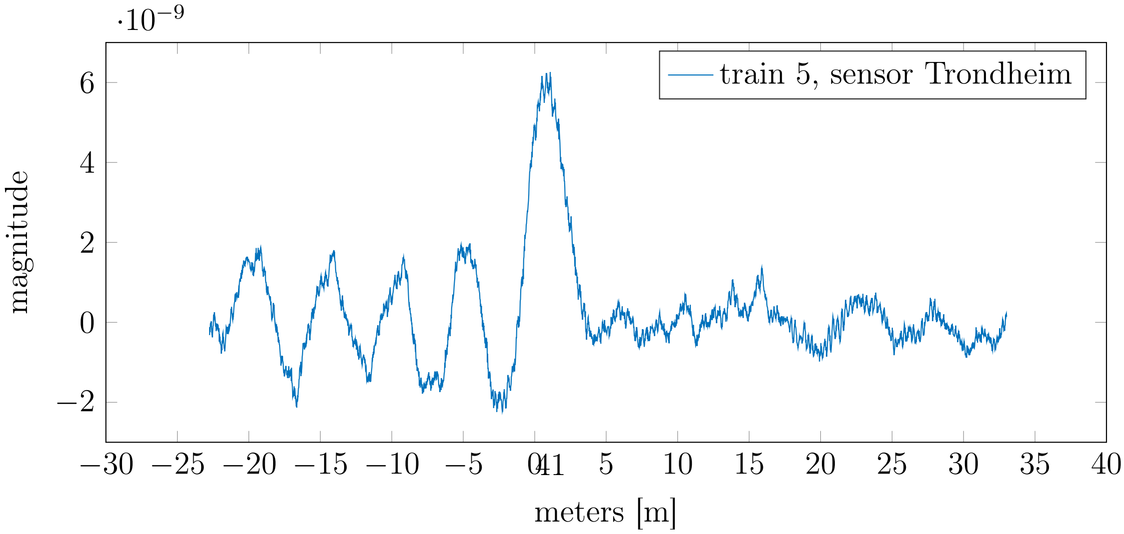
Figure 23: Influence lines train 4



(a) Influence line for sensor towards Heimdal, train 5

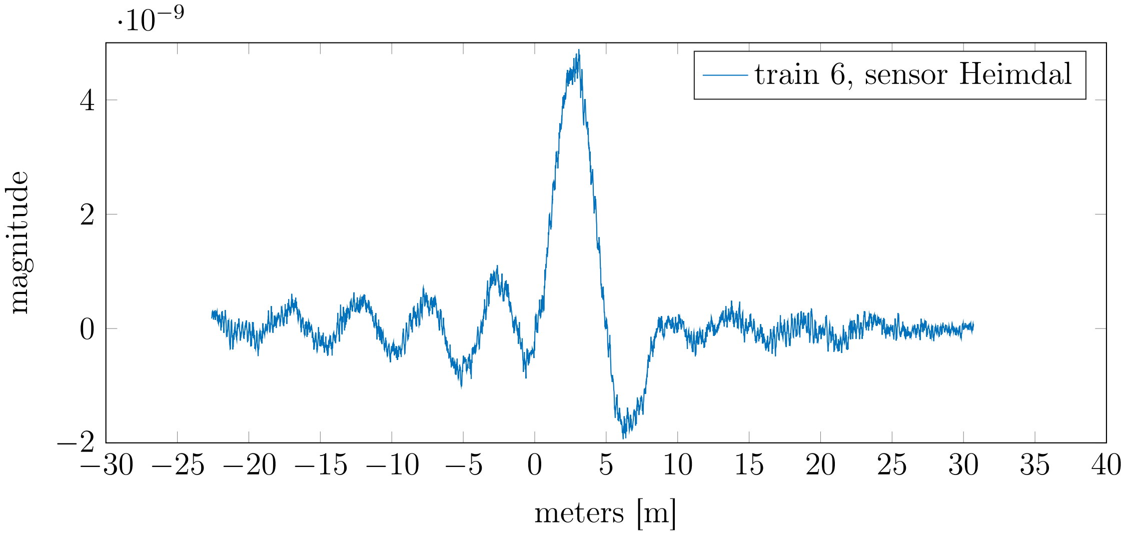


(b) Influence line for middle sensor, train 5

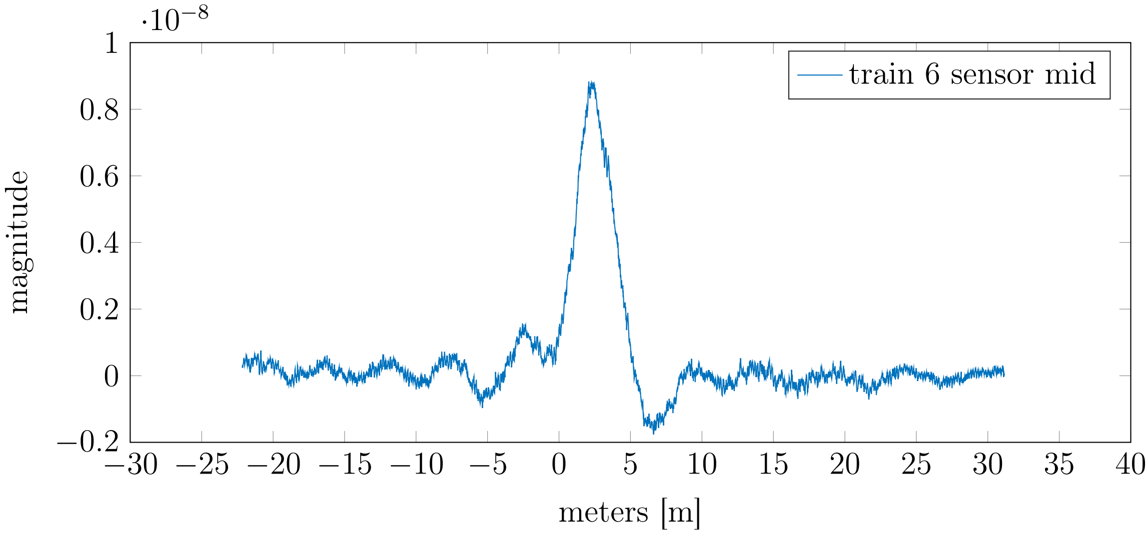


(c) Influence line for sensor closest Trondheim, train 5

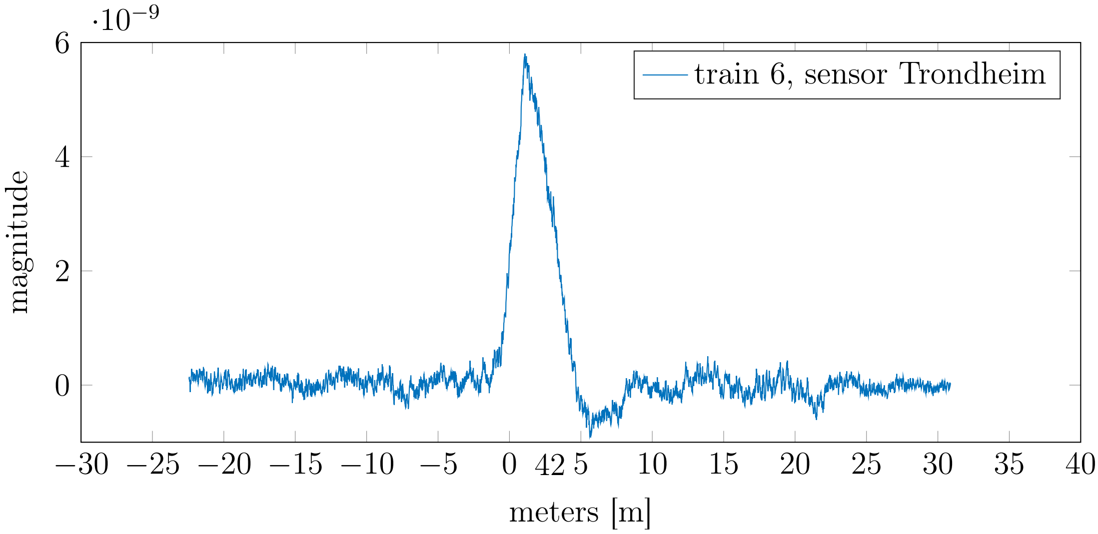
Figure 24: Influence lines train 5



(a) Influence line for sensor towards Heimdal, train 6

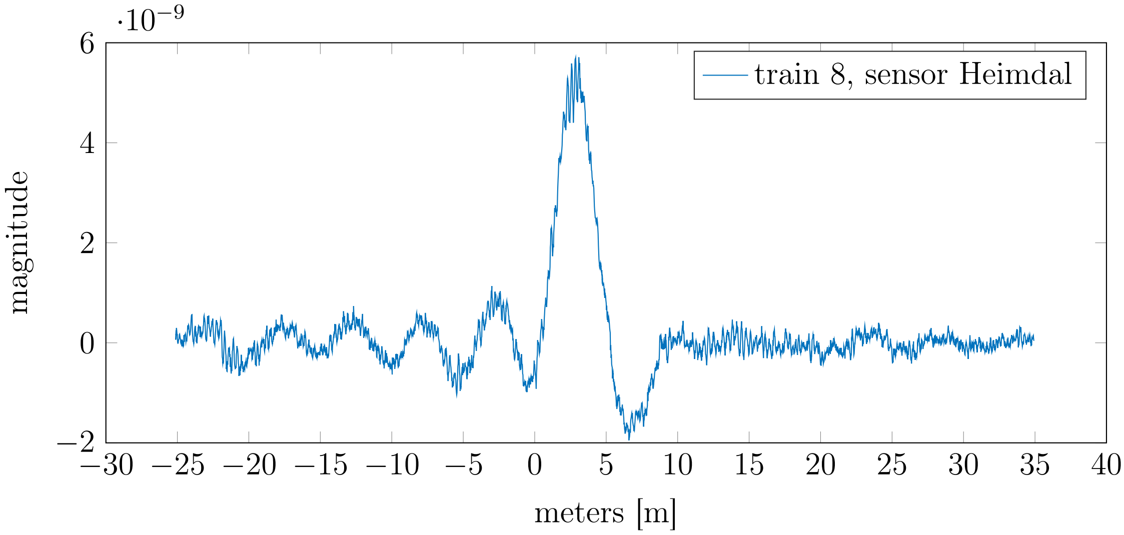


(b) Influence line for middle sensor, train 6

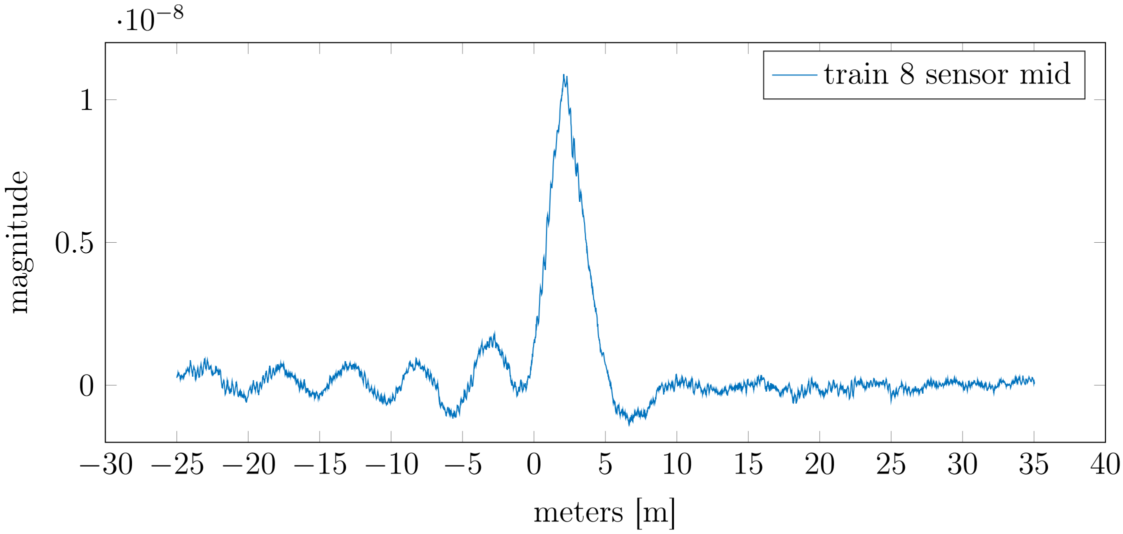


(c) Influence line for sensor closest Trondheim, train 6

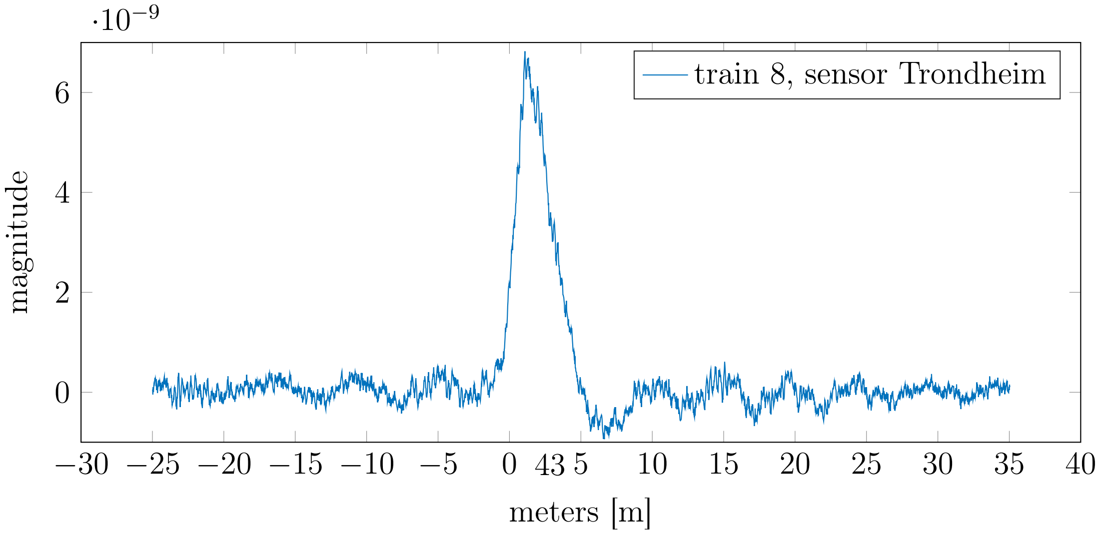
Figure 25: Influence lines train 6



(a) Influence line for sensor towards Heimdal, train 8

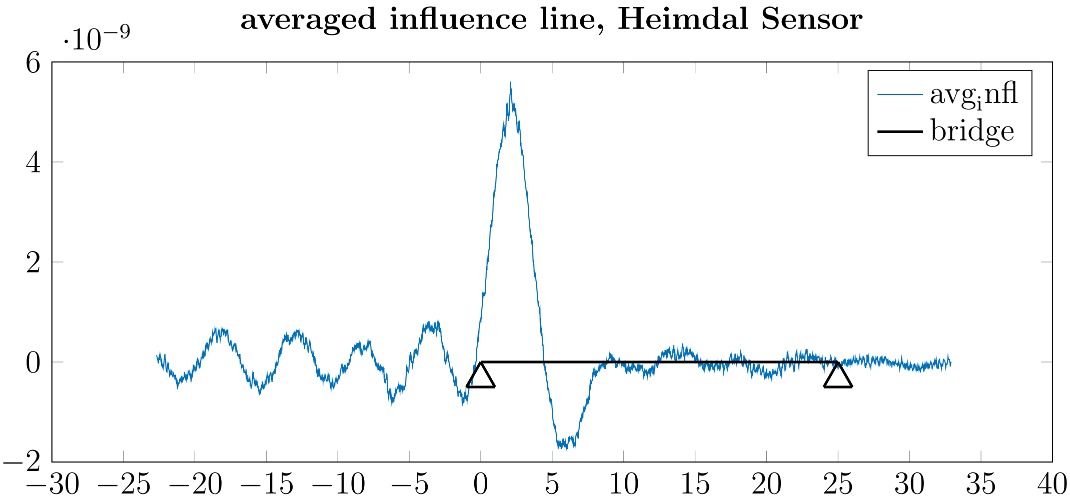


(b) Influence line for middle sensor, train 8

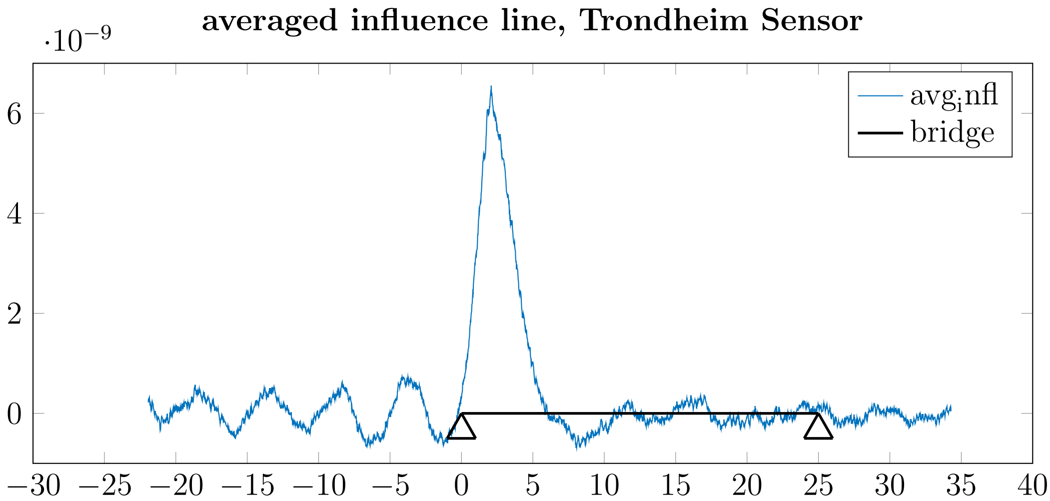


(c) Influence line for sensor closest Trondheim, train 8

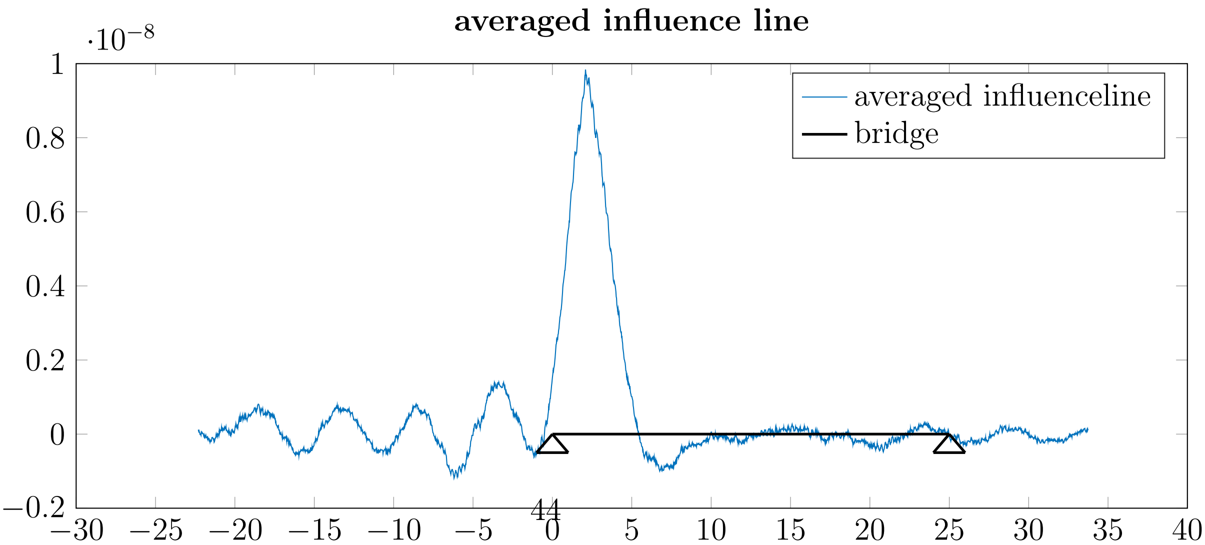
Figure 26: Influence lines train 8



(a) Averaged Influence line for sensor towards Heimdal



(b) Averaged Influence line for sensor towards Trondheim



(c) Averaged Influence line for middle sensor

Figure 27: Influence lines train 8