# Single point methods for determining blast wave injury

Jan Arild Teland, Ans van Doormaal, Marike van der Horst and Eirik Svinsås

Norwegian Defence Research Establishment (FFI)

12 January 2011

FFI-rapport 2011/00130

112001

P: ISBN 978-82-464-1878-0
E: ISBN 978-82-464-1879-7

## Keywords

Sjokkbølge

BTD

Skade

Numerisk simulering

Enkeltpunktsmetode

## Approved by

| | |
|---|---|
| Eirik Svinsås | Prosjektleder |
| Jan Ivar Botnan | Avdelingssjef |

## English summary

Models for calculating human injury from a blast wave are examined. The Axelsson BTD model is able to give injury estimates also for complex shock waves, but is difficult to use in practise since it requires input from four pressure sensors on a BTD (Blast Test Device) in the specific location. To find the injury in other places, a new experiment or simulation has to be performed.

However, several SP (Single Point) methods for injury calculation are seen to exist, where the side-on pressure history in the given location is the only required input parameter. To determine the accuracy of these models, a large numerical study was performed for various charge sizes at different distances. The estimates of the SP-models were compared with Axelsson BTD and in general seen to be in good agreement.

## Sammendrag

Vi undersøker aktuelle modeller for å beregne skade på mennesker forårsaket av sjokkbølger. Axelsson BTD modellen viser seg å gi estimater for skade av en hvilken som helst sjokkbølge, men er vanskelig å bruke i praksis da den krever fire trykkmålinger fra sensorer på en BTD (Blast Test Device) i den aktuelle posisjonen. For å finne skaden i andre punkter må enten et helt nytt eksperiment eller en helt ny simulering gjennomføres.

Imidlertid finnes det flere SP (Single Point) metoder for beregning av skade, hvor man bare trenger side-on trykket som funksjon av tid i den gitte posisjonen. For å sjekke nøyaktigheten til disse modellene ble det gjennomført en omfattende studie med numeriske simuleringer av en lang rekke ladningsstørrelser på forskjellig avstand. Estimatene til SP-modellene ble sammenlignet med resultatene fra Axelsson BTD og var generelt i god overensstemmelse.

# Contents

# 1 Introduction

Determining the human injury from a given explosion is a challenging problem. Currently, one of the greatest threats to armed forces participating in international operations is the IED (Improvised Explosive Device). The effect of IEDs therefore has become the focus of a lot of research, with the main goal of protecting personnel against the threat.

Explosions can cause injury in a number of ways, in particular through blast wave interaction and fragment impact. In this report we will focus only on injuries due to blast waves. To see how this fits into the total picture, Figure 1.1 gives a schematic overview of the IED problem divided into the various subproblems. The component examined in this report is highlighted in red, while components that have been investigated earlier at FFI are marked in green.

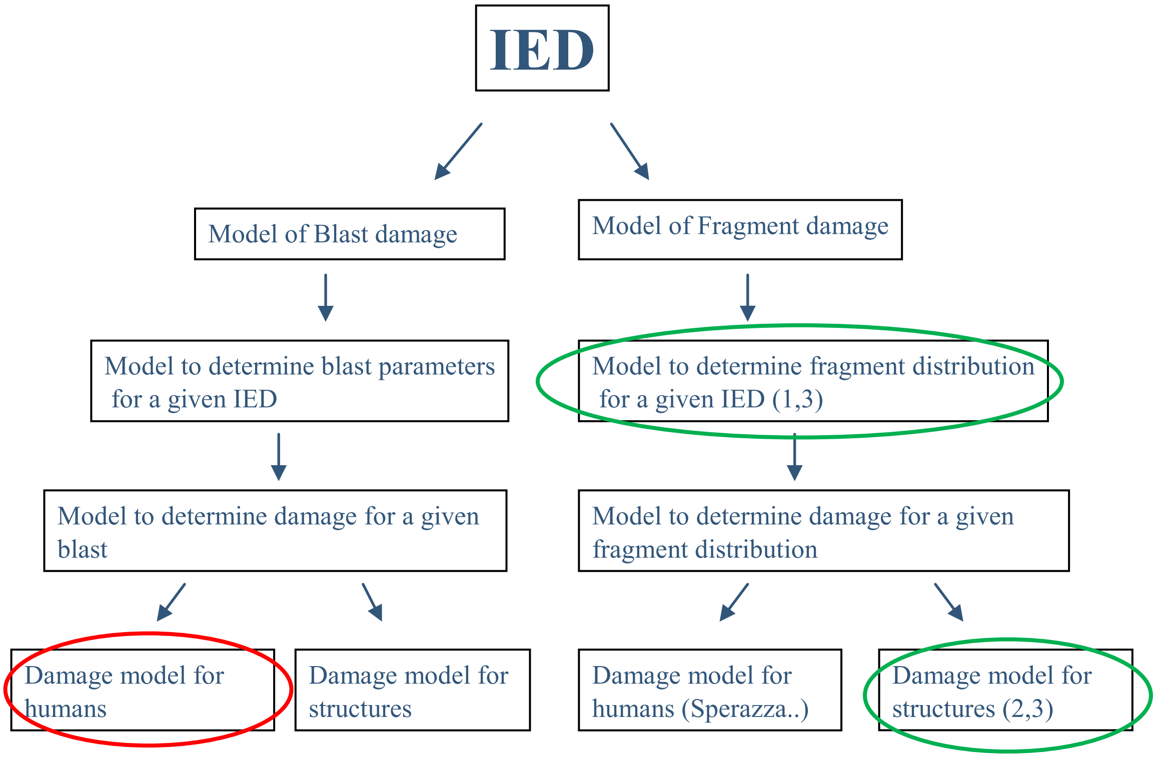



*Figure 1.1 Schematic overview of the IED problem divided into subproblems.*

The actual blast wave injury depends on many parameters like the size and composition of the bomb, the location of the human relative to the bomb, the geometry of the surrounding area etc. Further, the exact injury mechanisms in humans are not completely understood. As a consequence, it is very difficult to solve the problem analytically. A direct experimental approach to determine injury on humans is obviously not possible either.

In this report we will examine several approaches to see what options are available to determine the human injury from a given blast wave.

## 2 Bowen/Bass curves

Bowen (4) performed a huge number of animal experiments, in total involving 2097 animals of 13 different species, to determine the survival probability for subjects exposed to a free field blast wave. The blast waves were generated either by a detonation or from a shock tube. This resulted in a number of curves expressing the probability of survival as a function of maximum pressure P and blast wave duration T. A typical Bowen curve is shown in Figure 2.1.

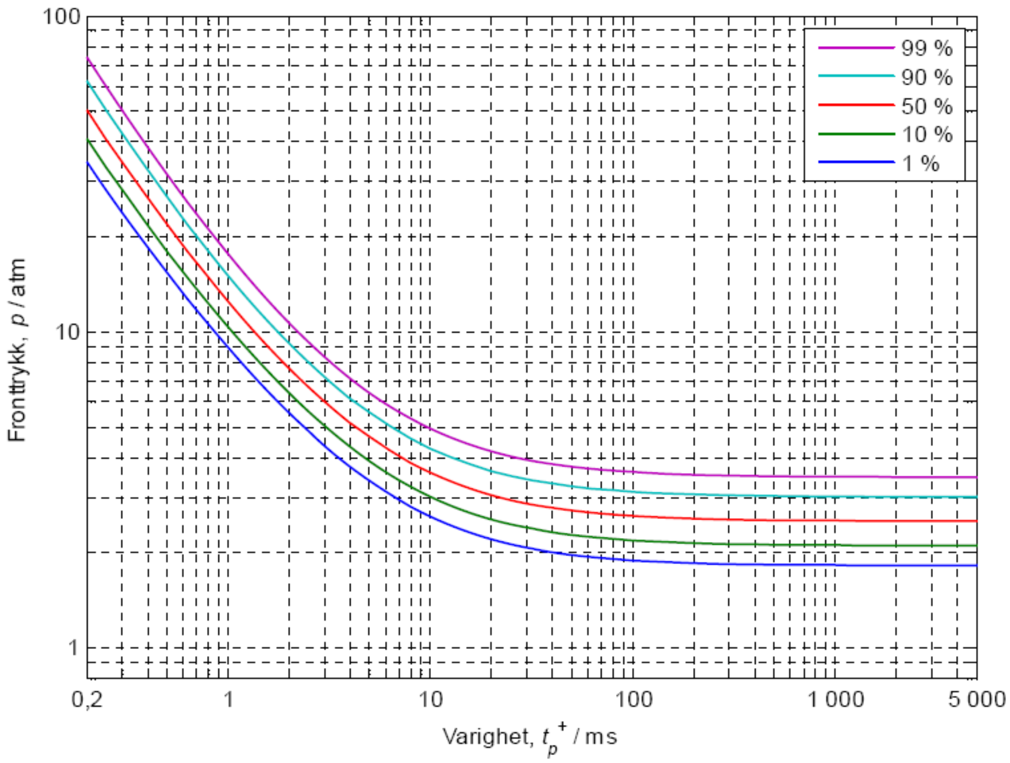



*Figure 2.1 Example of Bowen curves (from (5)) showing the probability of death as a function of blast wave duration T and maximum pressure P.*

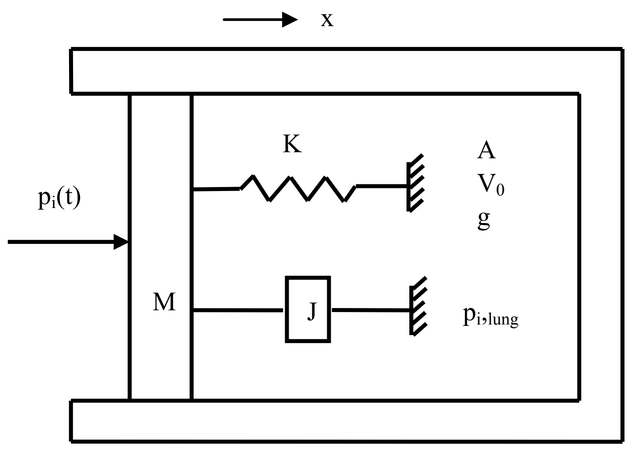
After scaling, it was thought that the results would be applicable to humans as well. Later, Bass (6) has included more data in the analysis to produce updated survival curves.

However, the Bowen/Bass formulas have several limitations. First, they assume a free field blast wave and are therefore not applicable to complex blast waves that develop in a situation where the initial wave can reflect against one or several walls/obstructions. Secondly, they only consider lethality and not injury risk. Finally, Bowen and Bass focused on lethality from lung injuries and neglected injuries to other body parts, such as the thorax and abdominal area.

# 3 Axelsson BTD

Axelsson (7) addressed these problems by creating a mathematical model which could take input data generated by a blast wave of any shape and provide an injury prediction for a person exposed to this wave. Besides lung injury, the Axelsson BTD model also accounts for injuries to the respiratory tract, the thorax and the abdominal area. (Stuhmiller (8) has developed a similar mathematical model[1], but since the actual model is not public, it will not be studied further here).

The Axelsson BTD model is a single degree of freedom (SDOF) system meant to describe the chest wall response of a human exposed to a given blast wave (Figure 3.1). The model requires pressure input data from four transducers located at 90 degrees interval around a 305 mm diameter Blast Test Device (BTD) (Figure 3.2), exposed to the relevant blast wave.




| Name | Explanation |
|---|---|
| A | Effective area |
| M | Effective mass |
| $V_0$ | Lung gas volume at x=0 |
| J | Damping factor |
| K | Spring constant |
| $p_0$ | Ambient pressure |
| $p_i(t)$ | External (blast) loading pressure |
| $p_{i,lung}(t)$ | Lung pressure |
| g | Polytropic exponent for gas in lungs |
| x | Chest wall displacement |

*Figure 3.1 Mathematical model of the thorax according to Axelsson [3]*

[1] Actually, the Stuhmiller model was initially published in open literature (8), but the original article contains at least two errors in the differential equation for the model, making it impossible to apply. In private correspondence, Stuhmiller says these errors have been corrected in later versions of the model and that the model itself has "evolved significantly" since then, though the correct differential equation remains secret for the time being.

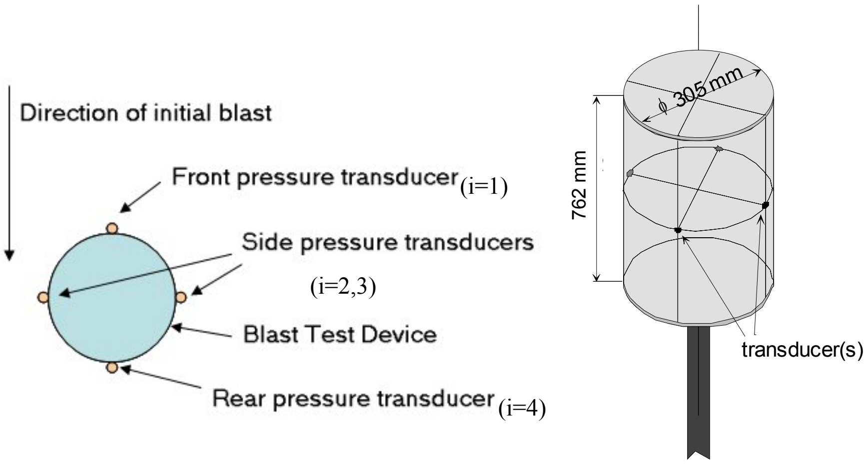



*Figure 3.2 Blast Test Device [3]*

The mathematical formulas for the Axelsson BTD model are expressed by four independent differential equations:

$$M \cdot \frac{d^2 x_i}{dt^2} + J \cdot \frac{dx_i}{dt} + K \cdot x_i = A \cdot \left[ p_i(t) - p_{i,lung}(t) \right] \qquad i = 1,2,3,4$$

$$p_{i,lung}(t) = p_0 \left( \frac{V_0}{V_0 - A \cdot x_i} \right)^g \qquad (3.1)$$

The values of the model parameters are given in the table below. However, it is not stated anywhere in Axelssons original article (7) how he arrived at these parameter values, so their derivation is a mystery for the time being.

*Table 3.1 Model parameters for the Axelsson BTD model*

| Parameter | Units | 70 kg body | Scaling Factor |
|---|---|---|---|
| M | kg | 2.03 | (M/70) |
| J | Ns/m | 696 | $(M/70)^{2/3}$ |
| K | N/m | 989 | $(M/70)^{1/3}$ |
| A | $m^2$ | 0.082 | $(M/70)^{2/3}$ |
| $V_0$ | $m^3$ | 0.00182 | (M/70) |
| g | | 1.2 | |

Input to the model are the four $p_i(t)$ pressure histories measured on the BTD. With this input, the differential equations can be solved for chest wall positions $x_i(t)$, chest wall velocities $v_i(t) = \frac{dx_i}{dt}(t)$ and lung pressure $p_{i,lung}(t)$ .

We see that there are no restrictions on the input pressure histories $p_i(t)$, so the Axelsson BTD model is not limited only to free field blast waves. However, unless the chest wall motion can be related to actual human injury, the model will not be of much use.

To find such a relationship, Axelsson started by examining the Bowen data. In the cases where the body was parallell to the direction of propagation of the blast wave, the blast load on the body should be almost equal to the incident blast wave, and the same for all four gauge points. Axelsson estimated the pressure histories $p_i(t)$ for many different blast waves on the same Bowen curves and solved Equation (3.1) with this as input. He noticed that the maximum inward chest wall velocity was reasonably constant for different combinations of P and T on the same Bowen curve. Since all these P and T combinations should give the same injury probability, this led Axelsson to assume that the maximum inward velocity was a good indicator of injury.

For the more general case, where the body is not parallell to direction of the incoming blast wave (and the various $p_i(t)$ therefore are different), Axelsson proposed the following quantity, called the Chest Wall Velocity Predictor ($V$), as a measure of injury:

$$V = \frac{1}{4}\sum_{i=1}^{4} \max\left(v_i(t)\right) \tag{2.2}$$

Several small charge experiments (0.907 kg and 1.361 kg C4) with anesthetized sheep in closed containers were then performed. After the experiments, the injuries of the sheep were assessed and a number ASII indicating the injury level was given in each case. From measurements on BTDs in sheep position, Axelsson found pressure input to his differential equation and was able to calculate the Chest Wall Velocity Predictor $V$. On plotting the corresponding $V$ and ASII points in the same diagram, Figure 3.3 was obtained.

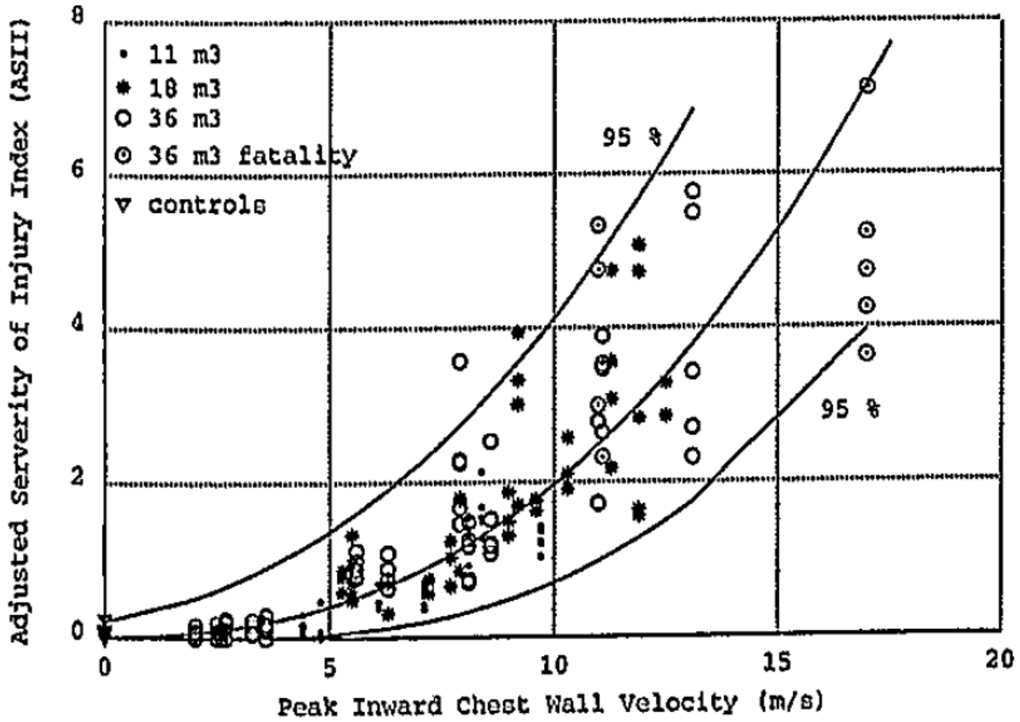



*Figure 3.3 Correlation between measured ASII and Chest wall velocity (from (7)).*

Evidently the experiments showed huge scattering, but from curve fitting Axelsson was able to derive the following correlation between ASII and V:

$$ASII = (0.124 + 0.117V)^{2.63} \tag{3.3}$$

The correlation between injury level, ASII and V are shown in Table 3.2. We see that the various regimes are overlapping due to the large uncertainties.

*Table 3.2 Correlation between injury level, ASII and V.*

| Injury Level | ASII | V (m/s) |
|---|---|---|
| No injury | 0.0-0.2 | 0.0-3.6 |
| Trace to slight | 0.2-1.0 | 3.6-7.5 |
| Slight to moderate | 0.3-1.9 | 4.3-9.8 |
| Moderate to extensive | 1.0-7.1 | 7.5-16.9 |
| >50% Lethality | >3.6 | >12.8 |

The Axelsson BTD model solves the problems mentioned with the Bowen/Bass approach, but unfortunately the price is added complexity. The main problem is that to calculate the injury level in a given position, it is not enough to know the single point (side-on) pressure histoty at that location. Instead the Axelsson BTD model requires four pressure histories acquired by pressure transducers placed on a cylindrical Blast Test Device (BTD). These pressures can be determined either in a physical test setup or in a numerical environment.

Clearly, the BTD procedure complicates things considerably since each experiment or simulation can only predict injury at the BTD location. For a different position, the simulation would have to be re-run with the BTD in the different place. To determine the injury risk as a function of position in a larger area according to the Axelsson BTD model therefore requires a huge number of experiments or simulations.

A model which only takes the single point (side-on) pressure as input would therefore be welcome. Fortunately, as we shall see, there are a number of these single point (SP) models available. In the rest of this report we will examine them closely to see whether they are good alternatives to the Axelsson BTD approach.

In the following, the success of the SP models will be measured by how well their results compare with the Axelsson BTD model. Whether the Axelsson BTD model actually provides injury estimates that are physically correct, is a completely different issue, and will not be discussed in this report.

# 4 Weathervane SP

The Weathervane SP model (9) is an approach that tries, based on the single point (SP) field pressure, to estimate what the pressure would have been for the four sensors if a BTD had been present. The idea is illustrated in Figure 4.1.

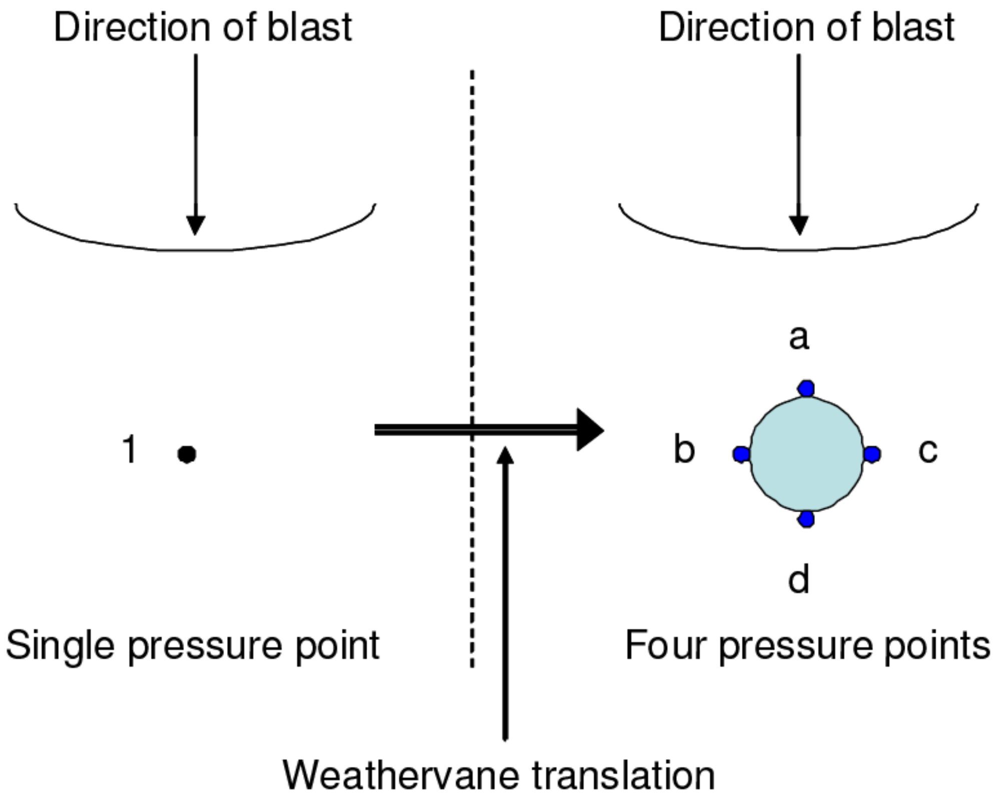



*Figure 4.1 Illustration of the Weathervane SP model*

### 4.1 Overview

A fundamental assumption in the Weathervane SP model is that one of the (non-existing) pressure sensors always faces directly towards the blast wave. Given that, the procedure to estimate what the four sensors would have measured is as follows:

Sensor facing blast wave $p_1(t)$: Maximum pressure and total impulse are assumed equal to the reflected blast load on a rigid infinite wall. These values can easily be found analytically. The full pressure history $p_1(t)$ is then found by assuming a Friedlander form for the pressure wave and iterating the decay parameter until the total reflected impulse is correct (as calculated by ConWep (10)).

Side sensors $p_2(t)$ and $p_3(t)$: Assumed equal to the field (side-on) pressure.

Rear sensor $p_4(t)$: Assumed equal to the ambient pressure $p_0$.

These pressure histories are then used as input to the Axelsson BTD model (Equation (3.1)) for calculation of the chest wall velocity predictor *V*.

Let us now look a little more closely at the Weathervane model to check some of the assumptions and get a feeling for how it works.

## 4.2 Numerical study of Weathervane assumptions

Let us first study the the assumptions for determining maximum pressure in each of the four gauge locations. To do this we will perform numerical simulations using ANSYS AUTODYN 12.0 (11) to find the actual pressure distribution around a BTD being impacted by a blast wave. This will then be compared with the Weathervane estimates.

The numerical setup was in 2D planar symmetry using the Euler Multimaterial processor. A TNT charge of 20 mm diameter was detonated at a distance of 1750 mm from the center of the BTD (305 mm diameter). No walls were present. Gauge points were placed around the BTD at 5 degree intervals to measure the effect of placing the sensors at different locations on the BTD (as shown in Figure 4.2). From this we can find the maximum pressure as a function of the angle θ with the direction of the incoming blast wave. In addition, a simulation without the BTD, but with one gauge point in the center of where the BTD would have been, was performed in order to give single point input data to the Weathervane model.

It is to be hoped that the results for $p_{max}(\theta = 0)$, $p_{max}(\theta = 90)$ and $p_{max}(\theta = 180)$ are similar to what is given by the Weathervane estimates.

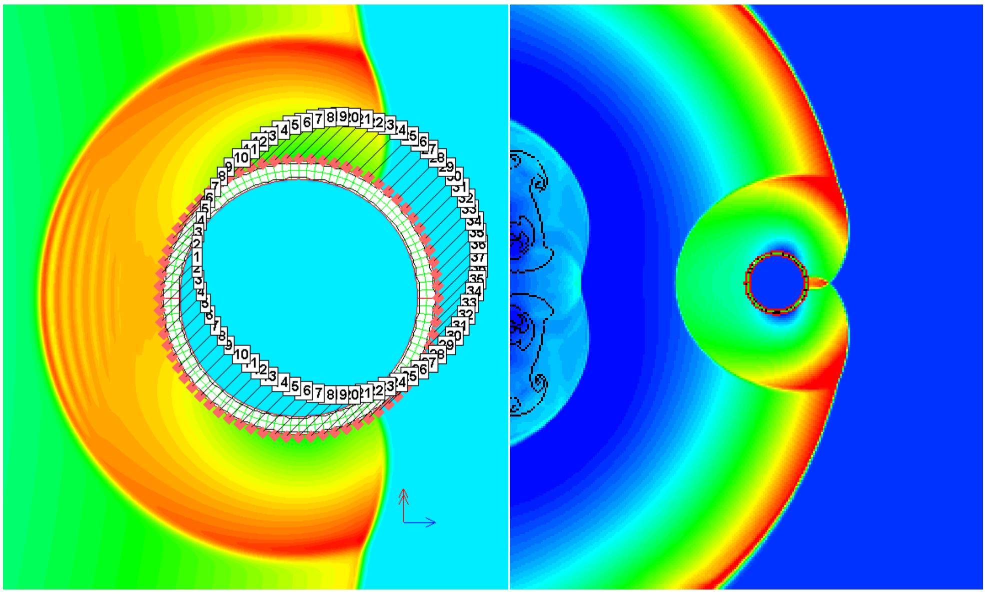


*Figure 4.2 Location of the gauge points and the pressure shockwave reflecting and refracting off the cylinder.*

The results for the maximum pressure in the BTD-simulations as a function of angle are shown in Figure 4.3, together with the Weathervane estimates. For the front pressure, we note that the Weathervane estimate is quite good but slightly lower than the BTD result. This may seem strange since the estimated result is for a perfectly reflecting wall. However, this can be explained by the front sensor being 152.5 mm (0.5 BTDs) closer to the detonation point, and thus the shock wave will have fallen off somewhat before reaching the gauge point in the center of the cylinder, from which the front sensor estimate is calculated. At distances further away from the detonation point, this should be less of a problem. We also note that the assumption of the 90 degree maximum pressure being equal to the maximum free field pressure looks very good. However, the pressure behind the cylinder is a bit higher than the assumed ambient pressure.

In order to actually calculate the chest wall velocity predictor using the Weathervane model, we need an estimate of the complete pressure history, not only the maximum pressure. From the procedure outlined in Chapter 4.1, we see that this is trivial to obtain for $p_2(t)=p_3(t)$ and $p_4(t)$. For the front sensor $p_1(t)$, the procedure is slightly more cumbersome involving an iteration process. The results are shown in Figures 4.4-4.6 compared to the results in the BTD simulation.

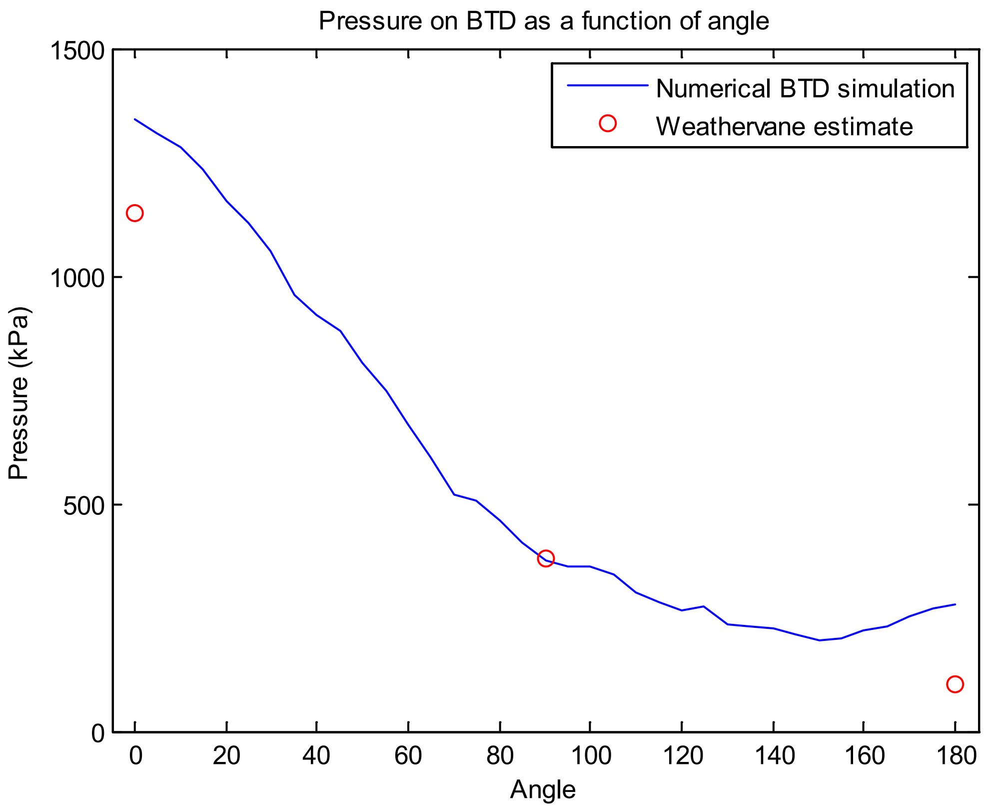



*Figure 4.3 Pressure on BTD as a function of angle together with the Weathervane estimate.*

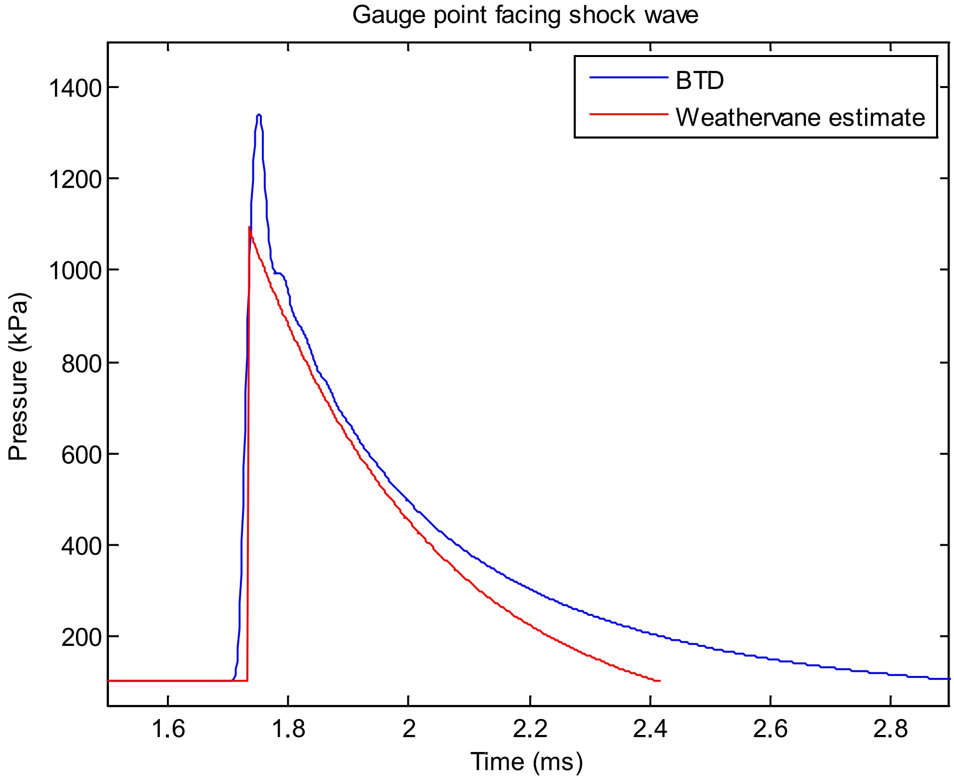



*Figure 4.4 Weathervane estimate for the front pressure on the BTD compared with the actual front pressure from the BTD-simulation.*

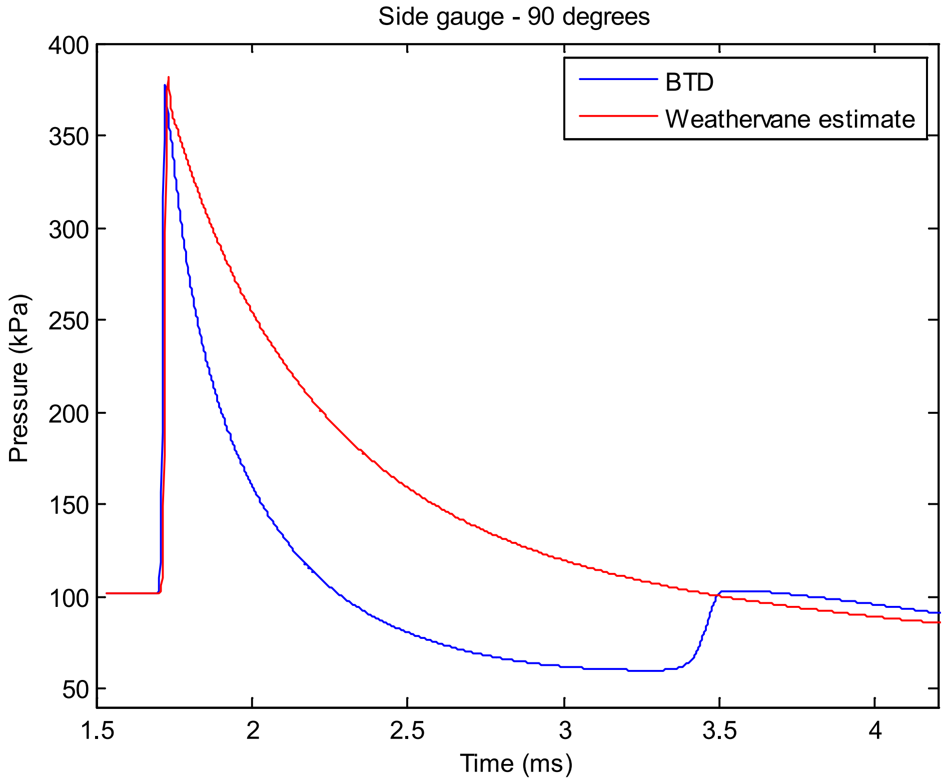



*Figure 4.5 Weathervane estimate for the side pressure on the BTD compared with the actual side pressure from the BTD-simulation.*

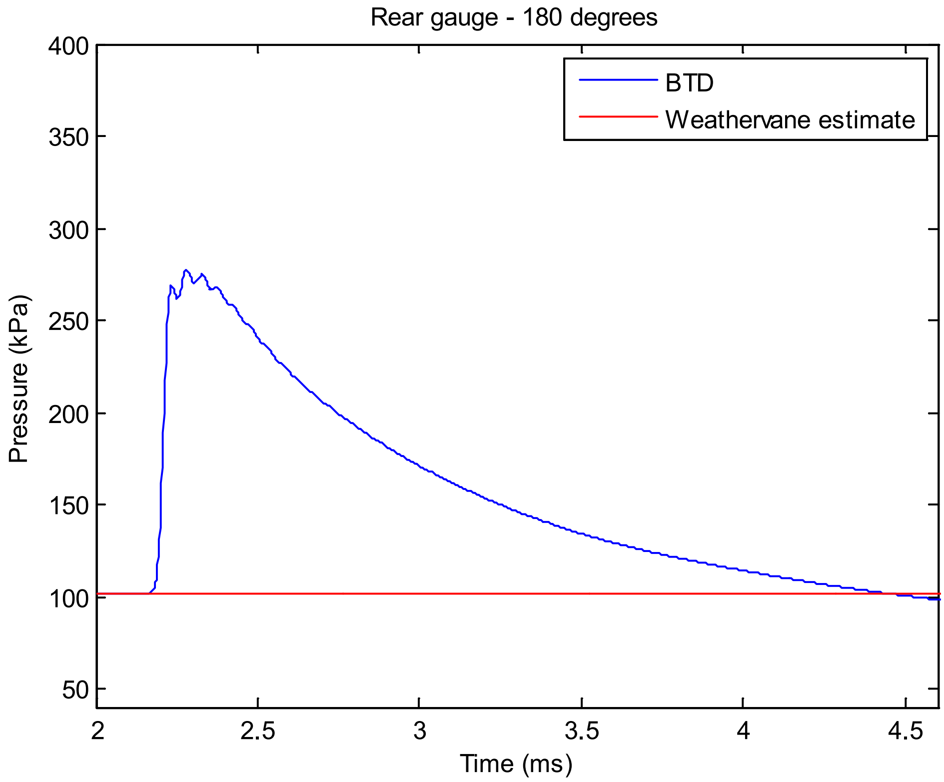



*Figure 4.6 Weathervane estimate for the rear pressure on the BTD compared with the actual rear pressure from the BTD-simulation.*

We note that the Weathervane estimate of the pressure history of the front sensor is quite good, although it seems to give a slightly shorter duration for the wave. The situation is opposite for the side gauge estimate, where the Weathervane estimate severely overpredicts the duration, even though the maximum pressure is in almost perfect agreement. Finally, for the rear gauge, the Weathervane estimate is far too low since it predicts no pressure at all.

Thus, we have both over- and underpredictions in the Weathervane estimates for the different pressure gauges. How does this affect the result for the chest wall velocity predictor, which is the quantity which we eventually are interested in? Table 4.1 shows the results for maximum chest wall velocity, calculated by insertion into the Axelsson differential equation (3.1).

*Table 4.1 Comparison between Axelsson BTD and Weathervane estimates*

| | **max($v_1$)** | **max($v_2$=$v_3$))** | **max($v_4$)** | **V** |
|---|---|---|---|---|
| **Axelsson BTD** | 9.32 m/s | 1.67 m/s | 3.45 m/s | 4.03 m/s |
| **Weathervane estimate** | 7.72 m/s | 3.58 m/s | 0.00 m/s | 3.72 m/s |

We note that the correspondence for *V* is very good as the too low front and rear velocities ($v_1$ and $v_4$) are mostly cancelled by the Weathervane side velocities ($v_2$ and $v_3$) being too high. Thus, the

Weathervane SP model appears to give results similar to Axelsson BTD, at least in the case studied here.

However, before proceeding, it might be of interest to examine the Weathervane assumption that the BTD will always have one gauge oriented towards the incoming blast wave. Clearly, the blast wave could arrive from any direction, at least in an environment with several reflecting structures. What if it turned out that the blast wave actually arrived at an angle of 45 degrees between two of the sensors? In that case it would not make much sense to label them front, side and rear? Would this make much difference to the chest wall velocity predictor *V* calculated? If it does, the Weathervane model might be in trouble.

From our BTD-simulations results we already have results from gauges at 5 degrees interval, which means the Weathervane assumption can easily be checked. Using p(θ), p(θ +90)= p(θ +270) and p(θ+180) as input to the Axelsson differential equation, is equivalent to having the blast wave arrive making an angle θ with the front sensor. By doing this for various angles, we can determine the chest wall velocity predictor V as a function of blast wave impact angle θ. The results are shown in Figure 4.7.

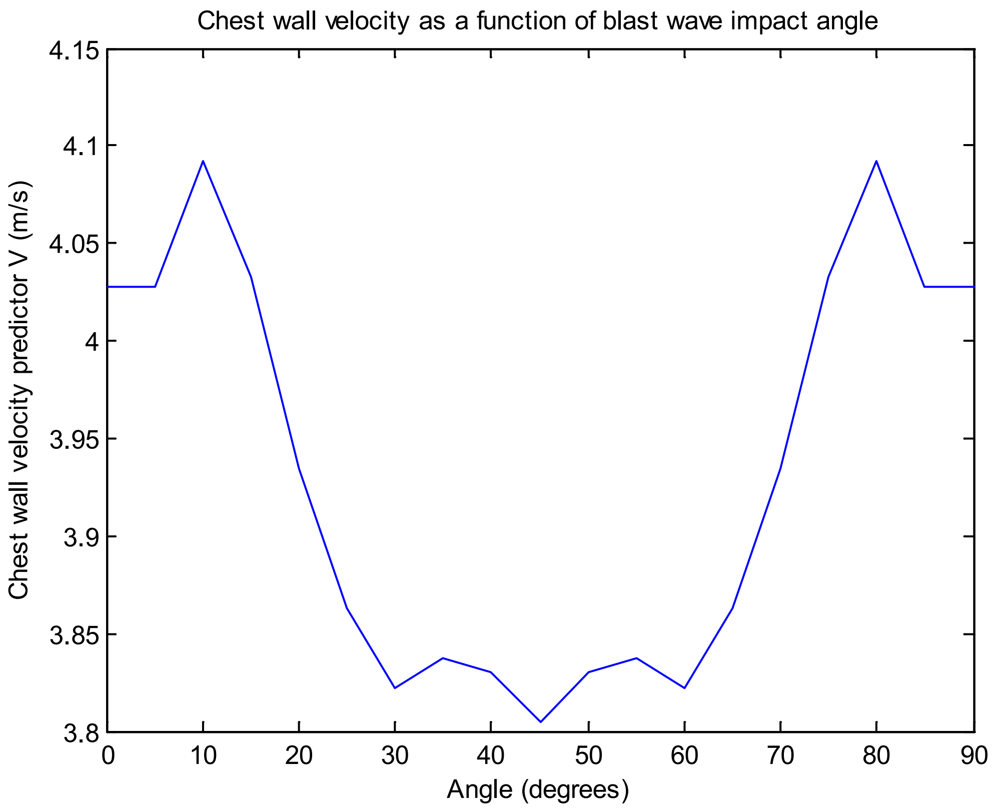



*Figure 4.7 Chest wall velocity predictor as a function of blast wave impact angle on BTD.*

From symmetry considerations we obviously have V(θ) = V(θ+90), so only the first 90 degrees are plotted. Note that the result for *V* is remarkably stable, ranging between 3.80 m/s and

4.10 m/s. Thus, the Weatherwane assumption where the V(θ=0) result is used seems very reasonable. (Especially compared with all the uncertainties already inside the original Axelsson BTD model).

In total, nothing so far indicates that the Weathervane SP model does not give reasonable values for the chest wall velocity predictor V. However, the example studied also indicates that the pressure histories of the individual gauges are not calculated very accurately, but that these errors tend to cancel each other out. Is this a coincidence for this particular example, or will this always happen? A more comprehensive study is needed before any of this can be proclaimed with certainty. In that study, we will, however, also include some other single point models.

# 5 Other Single Point models

In this chapter, we will outline some other single point models, i.e. models that are able to give an injury estimate without the need for a BTD.

## 5.1 Modified Weathervane SP

A problem with the Weathervane model is that finding the front pressure $p_1(t)$ is not straightforward, but involves a cumbersome iteration process to find the correct impulse. For implementation in a hydrocode this is inconvenient. To get around this, an alternative approach is possible, where the Friedlander waveform is not used, but instead the estimated sensor pressure $p_1(t)$ is assumed equal to the reflected pressure at each point in time. This will be called the Modified Weathervane model.

Thus, the estimates for $p_2(t)$, $p_3(t)$ and $p_4(t)$ are exactly the same as in the original Weathervane model, only $p_1(t)$ changes. Let us return to our example in Chapter 4 to see how this influences the result. In Figure 5.1 we plot the new estimate for $p_1(t)$ together with the actual BTD-result and the original Weathervane estimate.

We see that Modified Weathervane gives a pressure history which falls to zero a little bit slower than in the original model. It is also slightly higher than the BTD result, which seems to fall approximately in the middle, at least in this case.

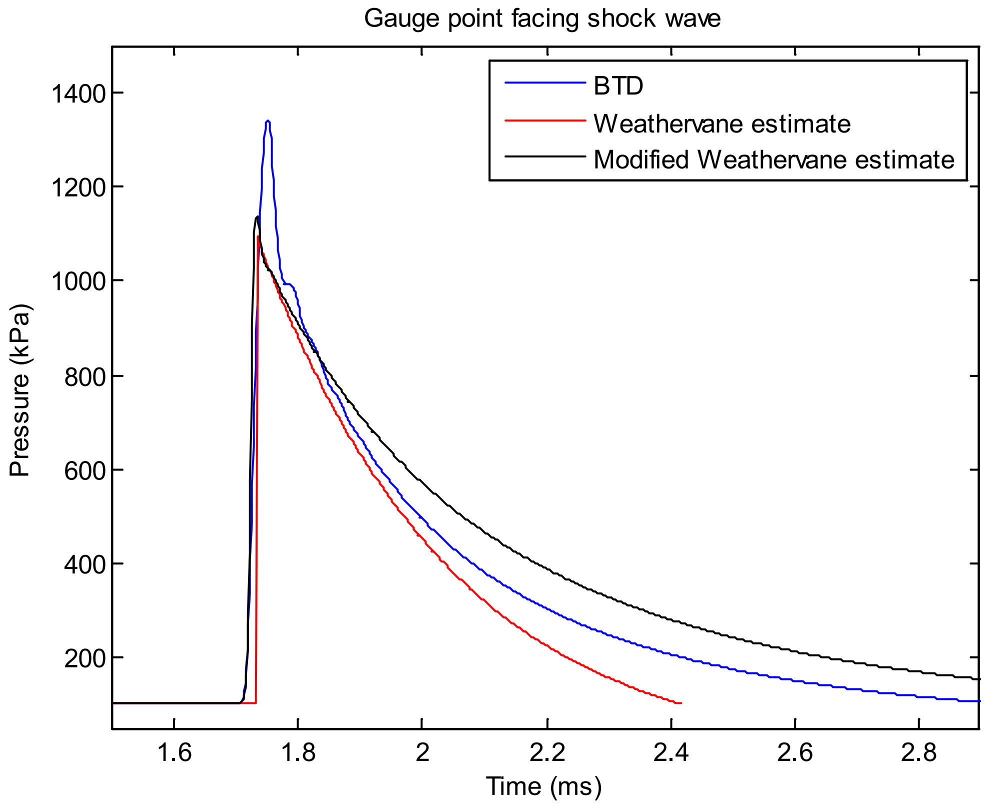



*Figure 5.1 Modified Weathervane estimate for the front pressure on the BTD compared with the actual front pressure from the BTD-simulation and the original Weathervane estimate.*

In Table 5.1 we have calculated the corresponding chest wall velocities from the Modified Weathervane model and compared them with the other models. We also note that, in this case, the BTD result seems to be in the middle between the two Weathervane models, but the agreement is still quite reasonable. In general, Modified Weathervane will always give slightly longer pulses and consequently somewhat higher estimates for the chest wall velocity predictor than the original model, but the differences will never be very large.

*Table 5.1 Comparison between Axelsson BTD and the Weathervane estimates*

| | **max($v_1$)** | **max($v_2$=$v_3$)** | **max($v_4$)** | **V** |
|---|---|---|---|---|
| **Axelsson BTD** | 9.32 m/s | 1.67 m/s | 3.45 m/s | 4.03 m/s |
| **Weathervane** | 7.72 m/s | 3.58 m/s | 0.00 m/s | 3.72 m/s |
| **Mod. Weathervane** | 10.77 m/s | 3.58 m/s | 0.00 m/s | 4.48 m/s |

## 5.2 Axelsson SP

The Axelsson SP model is just the Axelsson model without the BTD, but using the single point (SP) field pressure (i.e non-BTD) in the given location as input to the Axelsson differential equations. The four differential equations are then identical, so that $V = \max(v_1)$. This is not the way Axelsson intended for the model to be used, but it is still worth looking at what kind of results can be obtained.  In Table 5.2 we compare the chest wall velocity result from our example with the other models.

*Table 5.2 Comparison between Axelsson BTD and the Weathervane estimates*

| | **max($v_1$)** | **max($v_2$=$v_3$)** | **max($v_4$)** | **V** |
|---|---|---|---|---|
| **Axelsson BTD** | 9.32 m/s | 1.67 m/s | 3.45 m/s | 4.03 m/s |
| **Weathervane** | 7.72 m/s | 3.58 m/s | 0.00 m/s | 3.72 m/s |
| **Mod. Weathervane** | 10.77 m/s | 3.58 m/s | 0.00 m/s | 4.48 m/s |
| **Axelsson SP** | 3.58 m/s | 3.58 m/s | 3.58 m/s | 3.58 m/s |

Obviously the chest wall velocity results for the individual gauges are meaningless in the Axelsson SP model, but note that the total result for *V* is still quite close to the other models.

### 5.3 TNO SP

TNO has developed an approximation procedure of the Axelsson BTD model.  The method is fully described in (12).  Instead of solving the four differential equations, the Axelsson chest wall velocity predictor V is estimated from the main blast characteristics: peak pressures, the impulses, and the points in time of the different peaks (see Figure 5.2).  An exact pressure-time curve is not necessary.  The field (side-on) blast wave has been chosen as pressure input in this first exploration of the TNO SP method and its possibilities.

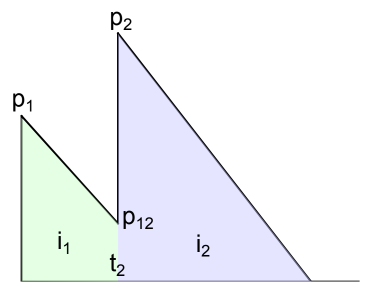



*Figure 5.2 Relevant characteristics of an arbitrary shock wave with two peaks, used for the approximation procedure of TNO (12)*

The full equations for V as a function of the blast characteristics are quite complicated and are therefore not repeated here.  Applying the model to our previous problem, we obtain a chest wall velocity of 4.87 m/s.  This is slightly above the other models, but considering the uncertainties in the Axelsson BTD model,well within the accepted range.  For completeness, Table 5.3 shows the TNO SP result together with the other models.

*Table 5.3 Comparison between Axelsson BTD and all SP models*

| | max($v_1$) | max($v_2$=$v_3$) | max($v_4$) | V |
|---|---|---|---|---|
| **Axelsson BTD** | 9.32 m/s | 1.67 m/s | 3.45 m/s | 4.03 m/s |
| **Weathervane** | 7.72 m/s | 3.58 m/s | 0.00 m/s | 3.72 m/s |
| **Mod. Weathervane** | 10.77 m/s | 3.58 m/s | 0.00 m/s | 4.48 m/s |
| **Axelsson SP** | 3.58 m/s | 3.58 m/s | 3.58 m/s | 3.58 m/s |
| **TNO SP** | - | - | - | 4.87 m/s |

We note that all SP models seem to provide results that are similar to Axelsson BTD. However, so far we have only examined one single scenario, so it is too early to draw any definite conclusions that this will always be the case. But, if we should find that any of these single point methods consistently produce injury estimates that are reasonably accurate compared with the Axelsson BTD model, they would considerably simplify calculations of expected injury in a complicated geometry.

# 6 Scenarios

In the next chapters we will investigate whether the various single point models actually are good approximations of the Axelsson BTD model. Of special interest is how they compare in complex blast situations, more particularly close to a wall. The comparison will be done by performing numerical simulations for a wide range of relevant cases.

A sketch of the simulation set-up is shown in Figure 6.1. In general the Axelsson BTD simulations consist of a BTD at different distances $x_2^j$ from a wall. To investigate both short and long blast pulses, charges are detonated at different distances $x_1^j$ from the BTD. Numerical pressure gauges around the BTD provide $p_i(t)$ input to the Axelsson BTD model. For the single point methods, an identical setup is used with the BTD replaced by one numerical pressure gauge, located where the center of the BTD would have been.

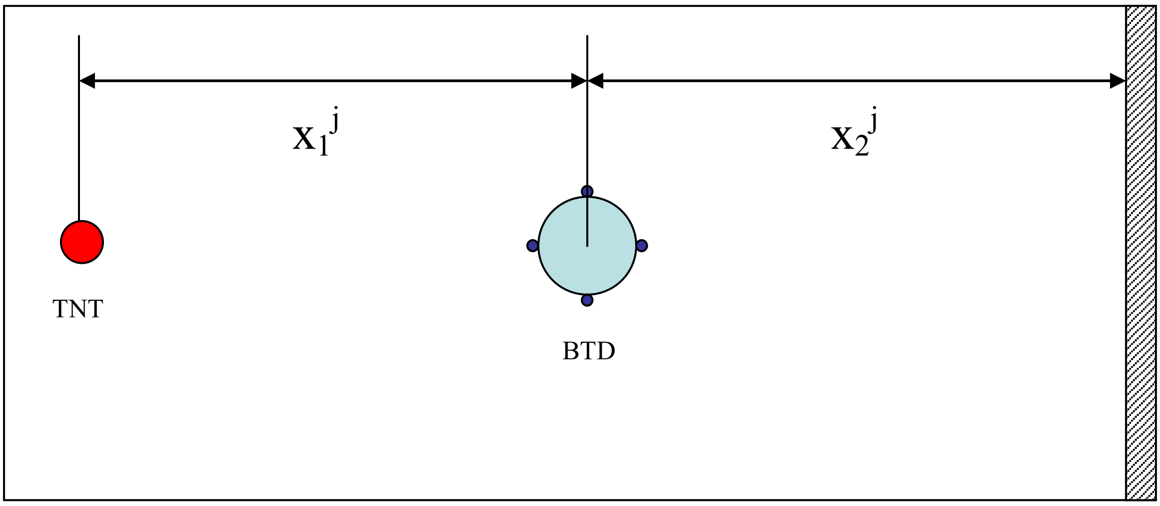



*Figure 6.1 Test setup with BTD, explosive charge on the left and wall on the right*

It was the intention to examine a wide variety of relevant scenarios, i.e. different charge sizes at different distances. Partly based on guidelines from STANAG 2280, the following charge scenarios were defined:

- 9 kg TNT (Large briefcase or body borne device)
- 20 kg TNT (Rucksack or suitcase)
- 200 kg TNT (Small car with explosives in the trunk)
- 400 kg TNT (Passenger vehicle)
- 1500 kg TNT (Van)

The most interesting scenarios are those with some chance of injury but where death is not guaranteed. To determine the charge distances for the simulation matrix, pressure data from CONWEP were used together with the lethality model of Bass (6), assuming no reflecting wall. Thus for all charges, two BTD-charge distances were determined: "Case 1: Safe distance" (i.e. threshold for lung injury) and the "Case 2: 50% probability of survival distance". In later simulations a wall was added at various distances $x_2^j$ . The basic simulation matrix is shown in Table 6.1.

*Table 6.1 Starting position for numerical simulations*

| Charge weight (j) | $x_1^j$ (safe distance) | $x_1^j$ (50% survivability) |
|---|---|---|
| 9 kg TNT | 5.4 m (110kPa at 5.07ms) | 3.4 m (300kPa at 3.50ms) |
| 20 kg TNT | 7.4 m (100kPa at 6.85ms) | 4.9 m (250kPa at 4.68ms) |
| 200 kg TNT | 18.9 m (70kPa at 16.34ms) | 12.4 m (170kPa at 11.51ms) |
| 400 kg TNT | 24.8 m (65kPa at 20.96ms) | 16.6 m (150kPa at 15.58ms) |
| 1500 kg TNT | 41.9 m (55kPa at 33.84ms) | 26.6 m (140kPa at 25.12ms) |

# 7 Numerical simulations in 3D

The following set-ups were compared in the simulations:

- Axelsson BTD (3D-simulation involving a BTD, with four gauges at 90 degrees interval).
- Axelsson SP (3D-simulation without BTD and only a single pressure gauge).
- Modified Weathervane SP (3D-simulation without BTD and only a single pressure gauge.)
- TNO SP (3D-simulation without BTD and only a single pressure gauge).

For simplicity the original Weathervane model was left out from the comparison.

All numerical simulations were run using ANSYS AUTODYN 12.0 in 3D. Earlier a subroutine had been written implementing the Axelsson SP model into AUTODYN. This was documented in (13), but after publication several improvements have been made. First, the Axelsson model is calculated for all grids in the simulation and not only one grid. Secondly, it has been extended to 2D grids and now works for both FCT and Multimaterial grids. Thirdly, several bugs were identified and removed. In the process a bug in AUTODYN which caused some user variables to be reset during the simulation was found.  Two "patches" were received from ANSYS to temporarily solve the problem until it was fixed in the next AUTODYN version.  Finally, the subroutine was extended to include the Modified Weathervane SP model as well.

With the help of this subroutine, the injury parameters could be calculated instantly for Axelsson SP and Modified Weathervane SP, instead of first running the simulation and then exporting the measured pressure data for processing. For the TNO SP model, the AUTODYN pressure history was exported to an Excel-file for processing.

In all cases, the numerical simulations were run using the following procedure:  The detonation and ensuing blast wave propagation was initially spherically symmetric, enabling us to calculate everything in 1D using a grid resolution of 7 mm.  The output from this 1D-simulation was then mapped into a coarser Euler Multi-material 3D grid when the situation was no longer spherically symmetric, i.e. when the blast wave reached the BTD.  For the 3D-simulations, a graded grid with a resolution of 7 mm around the BTD was used, but a coarser grid further away. The gauge points for the BTD were placed in the Euler grid right outside the BTD.

The air and detonation products were modelled using an Euler Multi-material grid, whereas the BTD was modelled as a rigid boundary on the Euler grid.  The standard air and TNT models from the AUTODYN material library were used.  Thus, air was modelled as an ideal gas and the TNT was modelled using the JWL-equation.

Example pressure plots from the 3D simulations are shown in Figure 7.1.  The gauge locations on the BTD are also indicated.  The following results have also been presented at the international MABS symposium (14).

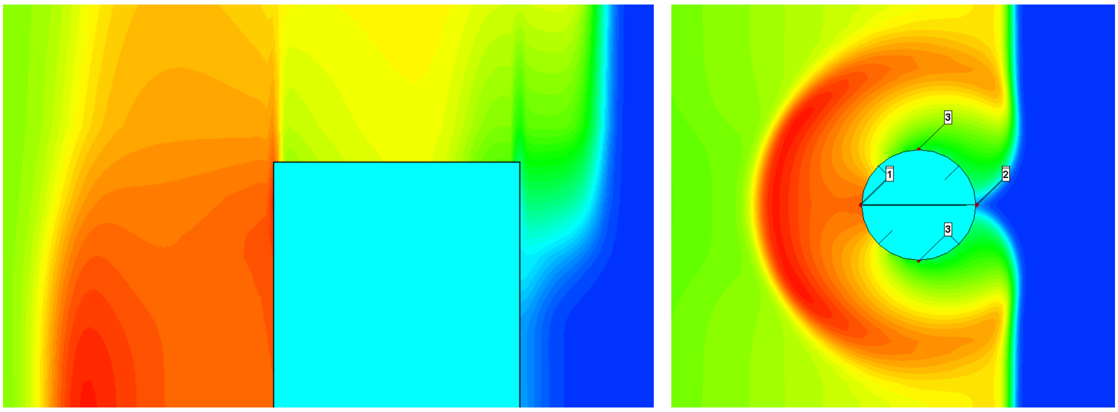



*Figure 7.1 Pressure plots in the 200 kg simulation from two different viewing angles (side and top)*

## 8 Preliminary 1D-simulations (safe distance)

When no wall or BTD is present, the whole scenario can be modelled using 1D. It is instructive to look at the actual pressures which are generated at the "safe" distance for the various charges. This is shown in Figure 8.1.

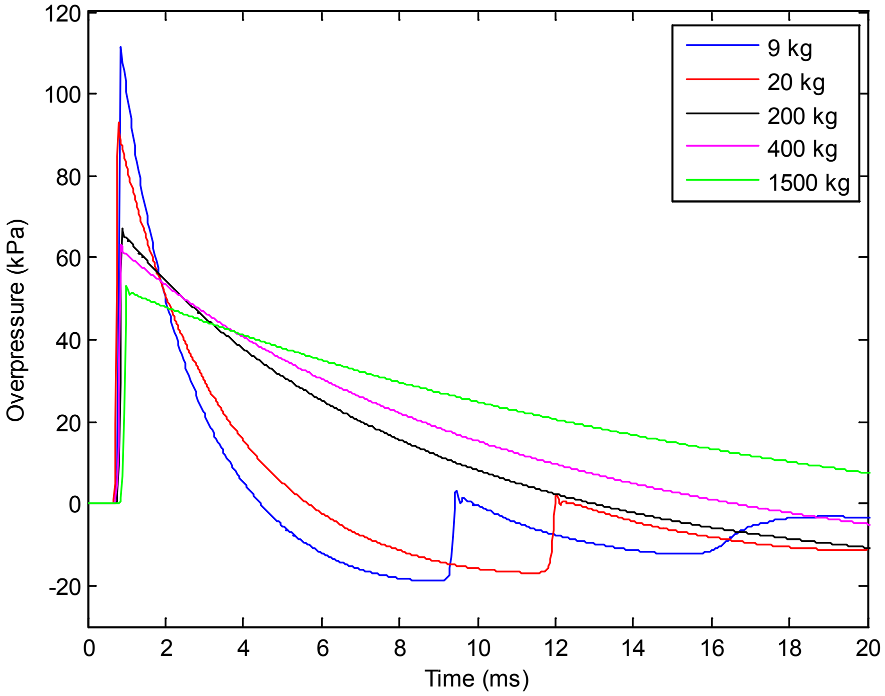



*Figure 8.1 AUTODYN pressure histories at safe distance (according to Bass [2]) for the various charges*

As expected, the shape of the pressure pulses are quite different, with the 9 kg pulse having a relatively short duration and high amplitude and the 1500 kg a lower amplitude but longer duration. Also, the pressure amplitude calculated by AUTODYN is very similar to what is predicted by CONWEP (Table 6.1), thus indicating that our simulations are in accordance with empirical results.

To get an idea of how the solutions of the Axelsson differential equations (3.1) depend on the pressure input, the Axelsson SP model has been applied to these pressure histories. The results for chest wall velocity are presented in Figure 8.2.

We note that in all cases the chest wall velocity has an oscillating form with the maximum velocity being reached for the first peak and the second peak being substantially lower (due to the linear damping term in the Axelsson equation). Despite the large difference in pressure input, the output chest wall velocities show very similar behaviour in the various cases. The duration of the first oscillation seems to increase somewhat with charge size, but not very significantly. The amplitudes of the first pulse (which determines the predicted injury) are also quite similar, which should be expected since the cases were selected exactly with that in mind. Thus, in that respect, Axelsson SP seems to be in good agreement with Bass. However, from a quantitative point of view, it should be noted that in all cases the maximum velocity falls below the Axelsson injury threshold value of 3.6 m/s.

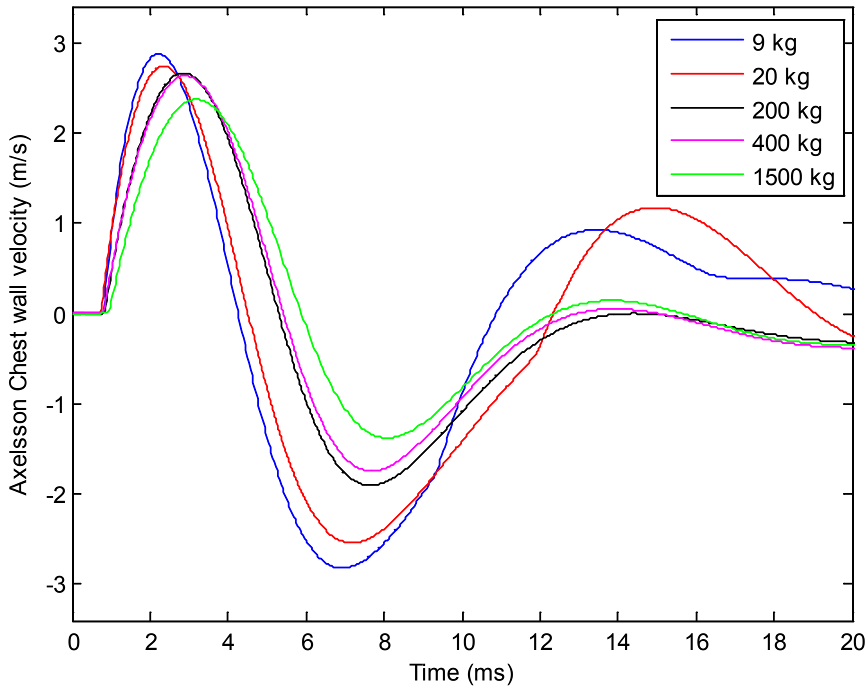



*Figure 8.2 Axelsson SP results for the various 1D pressure histories*

It is also noteworthy that the time for the "chest wall" to complete one "cycle" is not influenced much by the actual loading. Note especially that for 1500 kg the chest wall completes the first cycle long before the positive loading has ended. Thus, since the maximum chest wall velocity in the Axelsson SP model for a single blast wave always occurs on the first positive cycle, the injury calculated will be identical even if the 1500 kg pressure pulse had been suddenly cut off after 6 ms or later.

This property works to our advantage when dealing with blast waves of long duration, since only the first part of the pulse will be required to determine the maximum chest wall velocity. Consequently, it is not always necessary to model the whole blast wave, which reduces the number of elements. This property was exploited in the 3D-simulations to reduce computation time.

## 9 Results of 3D-simulations

In Figures 9.1 and 9.2 we present results for the maximum chest wall velocity, V, as a function of wall distance, calculated by the different methods from pressure data generated by the 3D AUTODYN simulations. The wall distance is measured in number of BTDs (1 BTD = 305 mm).

## 9.1 Case 1: Safe distance (according to Bass)

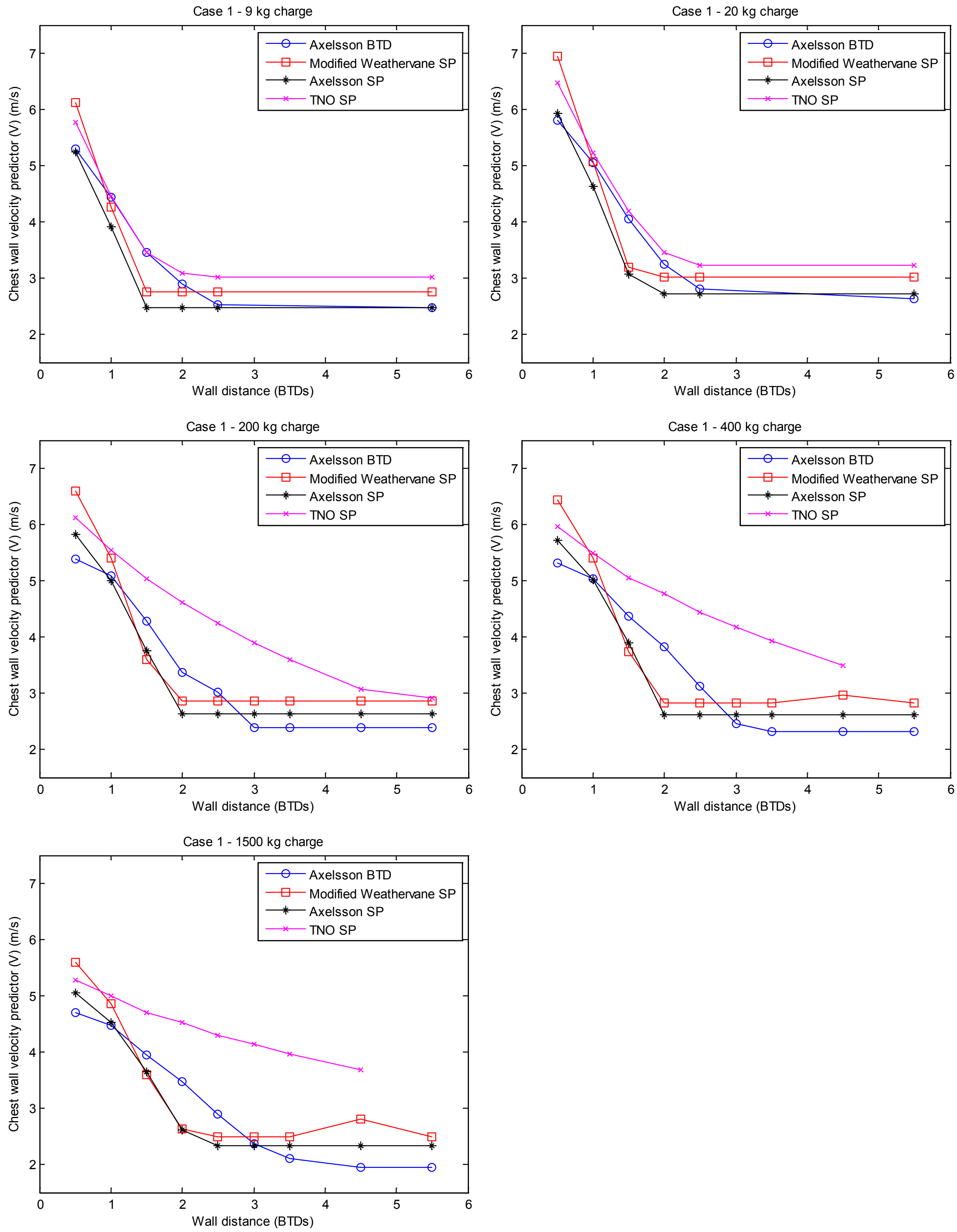



*Figure 9.1 Chest wall velocity predictor (V) for the different approache (Case 1: Safe distance according to Bass), based on 3D AUTODYN simulations*

## 9.2 Case 2: 50% survivability distance (according to Bass)

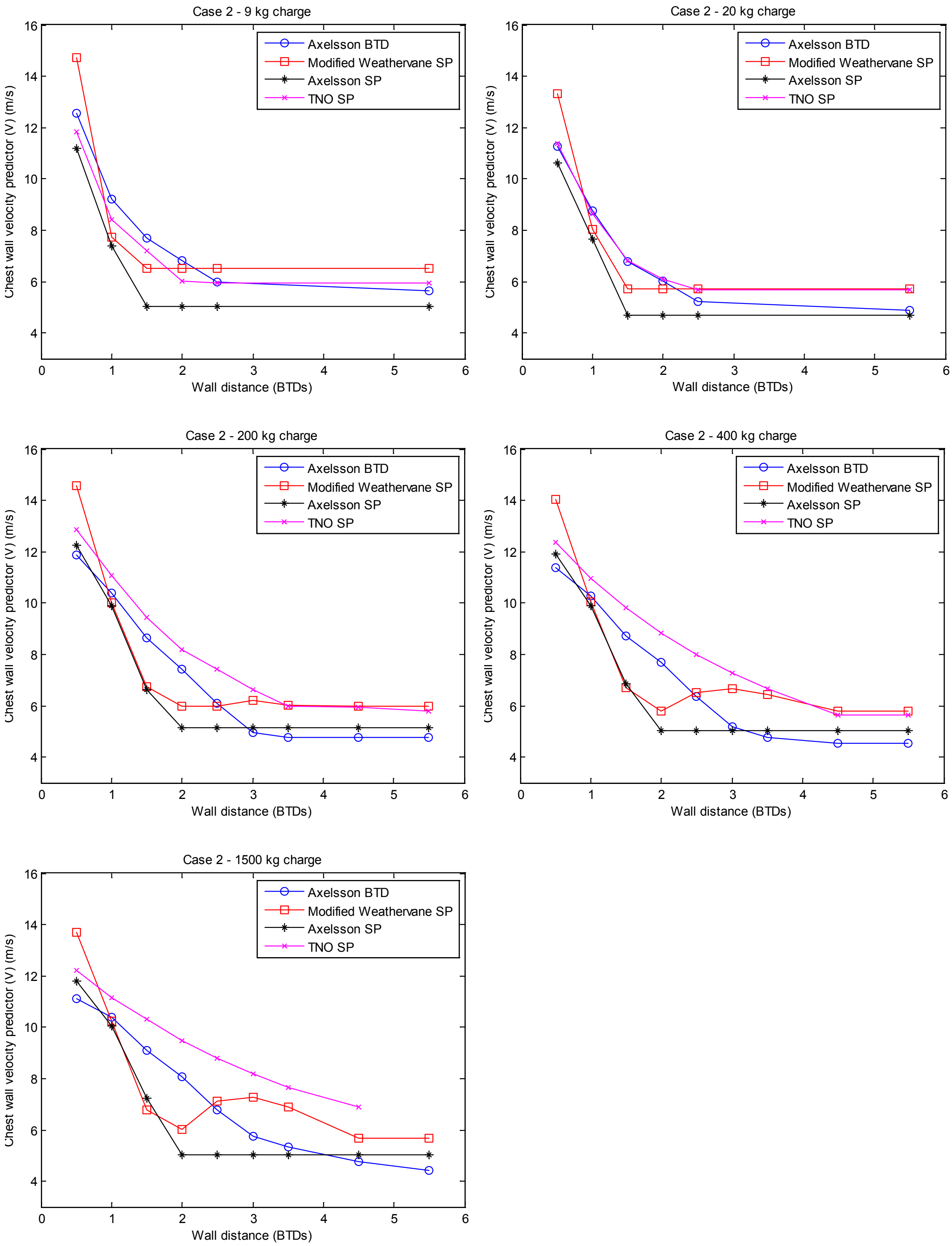



*Figure 9.2 Chest wall velocity predictor for the different approaches (Case 2: 50% survivability according to Bass), based on 3D AUTODYN simulations*

# 10 Discussion of 3D-results

The general impression from the results in Figures 9.1 and 9.2 is that all SP models to a large degree provide similar injury estimates to the Axelsson BTD method. This is especially clear when the large uncertainties in the relationship between the Axelsson chest wall velocity V and the injury indicator ASII is taken into consideration.

However, a closer inspection of the results reveals some interesting tendencies:

- For the two small charges (9 kg and 20 kg) the correspondence is particularly good for all SP methods independent of wall distance.
- For the larger charges (200 kg, 400 kg and 1500 kg) all SP models are quite accurate when either the wall is very close (0.5-1.0 BTDs) or far away (> 4.5 BTDs).
- At intermediate wall distances (around 1-3 BTDs), the methods diverge somewhat. Typically TNO SP will give the highest estimate of V while Axelsson SP gives the lowest estimate. TNO SP has roughly the same trend as Axelsson BTD, whereas Axelsson SP quickly decreases to a constant value. Modified Weathervane SP shows an apparently strange behaviour in this regime, especially in the 50% survivability case. The chest wall velocity predictor V does not decrease monotonically with wall distance, as one might have expected. After reaching a local minimum, it increases to a local maximum and then falls off again.
- Quantitatively, all models (including Axelsson BTD) predict less injury than Bass (6). The chest wall velocities should have been 3.6 m/s and 12.8 m/s for lung injury threshold and 50% lethality respectively, to be in agreement. However, these chest wall velocities are only reached when a wall is close behind the BTD, particularly for the 50% survival category, wheras according to Bass this should have happened even without a wall.

To explain the strange tendency of the Modified Weathervane SP, we need to look more closely at how the Axelsson mathematical model works. In Figures 8.1 and 8.2 we observe that a typical (one peak) blast wave, produced an oscillating motion of the chest wall. However, because of the damping term in Equation (3.1), the chest wall motion was attenuated, leading to gradually lower velocity amplitudes for subsequent cycles.

For complex blast waves, i.e. with two or more pressure peaks, the situation can be quite different. Depending on the amplitude and the time difference between the two peaks, the maximum chest wall velocity may occur on the second peak instead of the first. Figure 10.1 illustrates this situation in the Modified Weathervane case (1500 kg, 50% survivability).

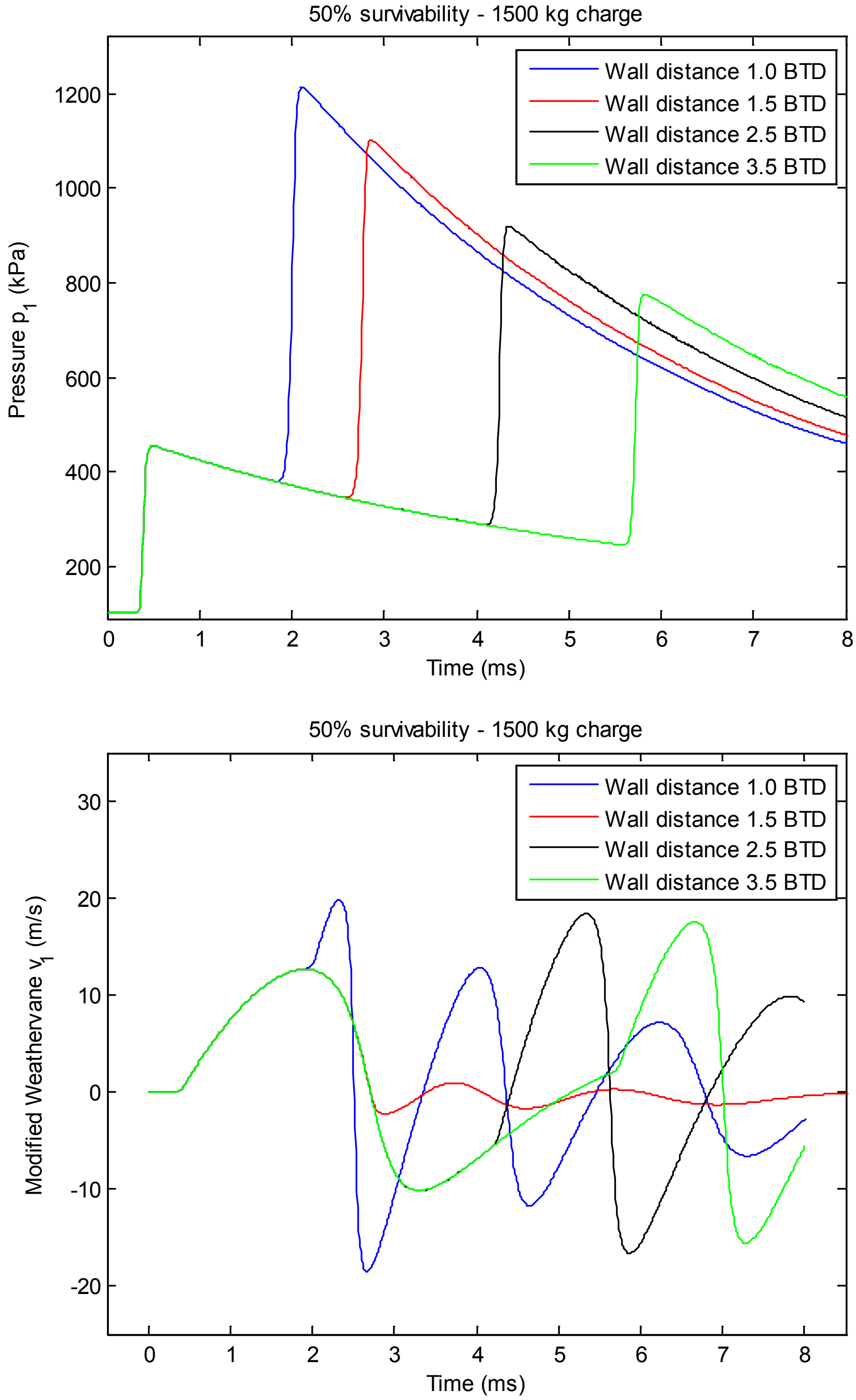



*Figure 10.1 Modified Weathervane chest wall velocity $v_1(t)$ for various wall distances*

The upper plot shows the pressure input $p_1(t)$ (i.e. the reflected pressure from a rigid wall, calculated from the free field pressure, as described earlier) as a function of time with a wall at various distances. As expected, the amplitude of the second peak decreases with wall distance. Intuitively one would therefore expect less injury further away from the wall, but the Axelsson model gives a different result. The lower plot shows $v_1(t)$ in Modified Weathervane SP (i.e. sensor assumed to be facing the blast wave) calculated from the pressure input in the upper plot.

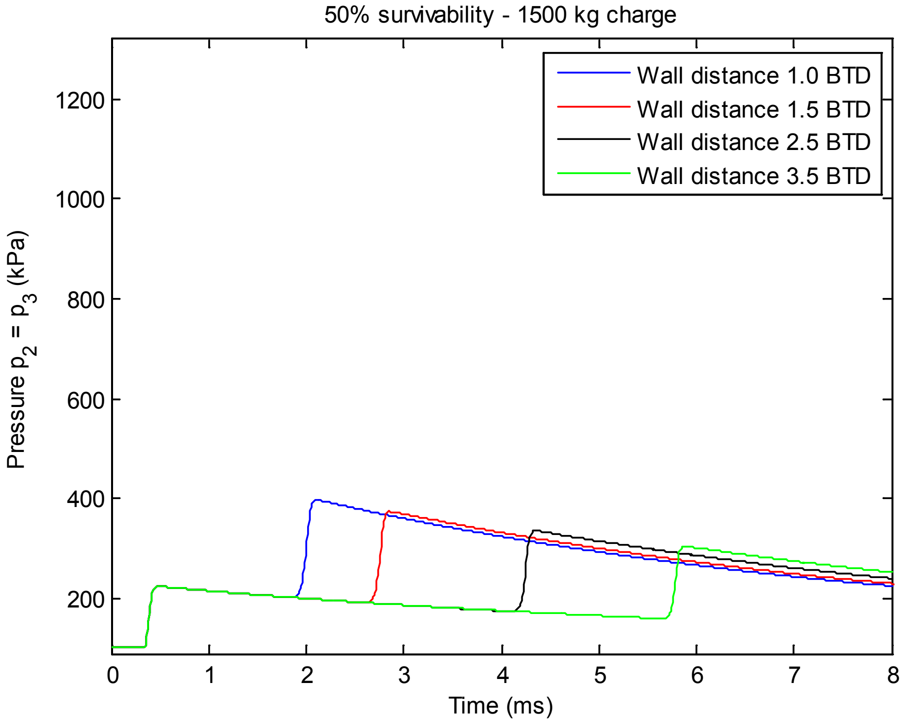
We see that for 1.0 BTD wall distance, the amplitude of the first velocity peak is increased due to the second pressure peak. However, at a distance of 1.5 BTD, the first cycle has almost been completed and motion is in the negative x-direction ("out-of- phase") when the second wave arrives and therefore it manages only to slow down the chest wall motion. However, if the wall is moved further away (2.5 BTD and 3.5 BTD distance), the second wave arrives on the second velocity cycle ("in phase") and increases the chest wall velocity amplitude to a higher value than for the first cycle. This "phase effect" explains the strange tendency of the Modified Weathervane SP model mentioned above.

One might have expected a similar effect for Axelsson SP, but this did not happen in any of our cases. An explanation is given in Figure 10.2, which shows the chest wall velocity output from Axelsson SP with the corresponding pressure input. (Remember that the Axelsson chest wall velocity is equal to the two components $v_2$=$v_3(t)$ in Modified Weathervane SP.)

On comparing the duration of one chest wall cycle in Modified Weathervane SP (Figure 10.1) and Axelsson SP (Figure 10.2), we note that it is longer for Axelsson SP. This feature, which is due to the higher pressure amplitude in the Modified Weathervane SP, will explain the different behaviour of Axelsson SP.

As expected, for 1.0 BTD wall distance, the amplitude of the first velocity peak is increased due to the second pressure peak. But, due to the longer duration of one chest wall cycle in Axelsson SP, at wall distance of 1.5 BTD and larger the results differ from Modified Weathervane SP. For 1.5 BTD distance, the second pressure peak arrives while the chest wall velocity is still near the local maximum and manages to push it slightly higher, but not higher than the velocity peak at 1.0 BTD. At a distance of 2.5 BTD the Axelsson SP gives roughly the same "out-of- phase" situation as was seen at 1.5 BTD for $v_1(t)$ in Modified Weathervane, where the second pressure peak only manages to slow down the chest wall motion. At distances larger than this (only 3.5 BTD is illustrated), the second pressure peak is again "in phase" with the chest wall motion, but then the wall is so far away that the pressure amplitude has fallen too much to enable the second velocity peak to go above the first peak.

As the phase effect is a feature of the Axelsson model itself, it will also happen in the Axelsson BTD model. However, it will not manifest itself so obviously in the chest wall velocity since Axelsson BTD depends on four different pressure signals (which are all different from the single point pressure pulse). Typically one signal will be out-of-phase and another in-phase, thus compensating for each other and diluting the phase effect.



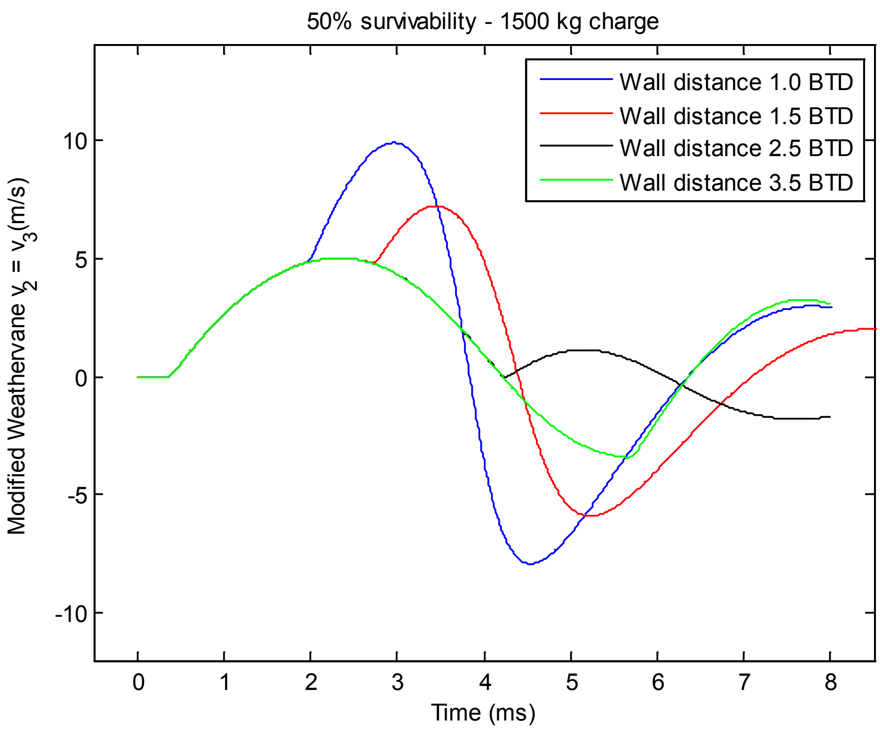




*Figure 10.2 Modified Weathervane chest wall velocity $v_2$=$v_3$(t) for wall at various distances (equal to the Axelsson SP chest wall velocity)*

Notice that it is the out-of-phase effect which causes Axelsson SP and Modified Weathervane SP to have a different trend than Axelsson BTD. The out-of-phase effect happens for all charges and it manifests itself more or less when the wall is at distances around 1.0-2.5 BTD by underestimating the BTD chest wall velocity. If these data points were ignored, a much better correspondence with the Axelsson BTD would have been obtained.

An obvious question is whether the "out-of-phase effect" actually is a real physical effect. The current results with the Axelsson BTD-model suggests it does not manifest itself in the injury levels. In the TNO SP model, the out-of-phase effect was deliberately ignored to be on the safe side, resulting in higher injury predictions in the intermediate regime (1.5-3.5 BTDs wall distance) than for the other SP models. If desirable, the TNO SP model could, in principle, be tuned to make it quantitatively in better agreement with the Axelsson BTD model.

# 11 Results for individual gauges in Modified Weathervane SP

Having seen that Modified Weathervane SP gives reasonable estimates of the Axelsson BTD chest wall velocity predictor V, the predictions for each individual gauge are studied as well. The idea behind the Weathervane method is, of course, to predict what would have been measured on a BTD if it had been present. As an example, we look at the 1500 kg "50% survivability" case and compare individual gauge results for Axelsson BTD and Modified Weathervane SP. This is illustrated in Figure 11.1.

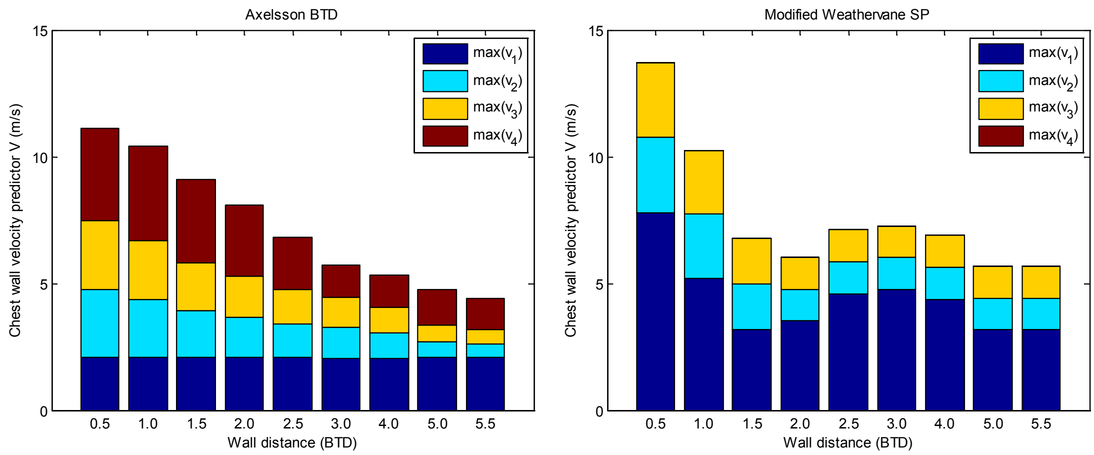



*Figure 11.1 Comparison of results from Axelsson BTD and Modified Weathervane SP for individual gauges*

We note that the correspondence between the two methods is not very good at all for the individual gauges. Modified Weathervane SP produces much too high results for the front gauge, particularly when there is a wall present. (The original Weathervane model will do slightly better by producing lower results). Note that the front gauge of Axelsson BTD gives almost a constant value as it sees a relatively weak second peak because of shielding by the BTD itself. In an SP model, obviously there can be no such effect. This shows clearly that it is the second peak which causes the high velocity $v_1$ in the Weathervane SP model.

The assumption in the Weathervane model of ambient pressure behind the BTD is also clearly not correct. In fact, the maximum chest wall velocity from the Axelsson BTD rear sensor is seen to be almost consistently higher than from any of the side sensors. This is natural when a wall is present, since the pressure becomes very high when the shock is reflected from the wall and then reflected at the rear end of the BTD again. However, even without a wall, the rear sensor makes a non-negligible contribution.

Fortunately, as we see, the errors to a large degree cancel each other out, leading to a reasonable estimate for the chest wall velocity predictor V. Only the out-of-phase effect, which is obvious here too, is not cancelled out. Results from other charge weights are similar.

## 12 Conclusions

Numerical simulations comparing various single point (SP) approaches with the Axelsson BTD method have been performed. A variety of relevant cases were examined, ranging from small charges at a short distance to large charges far away, for both free field situations and complex blast (by the presence of a wall behind the target).

Generally the single point methods gave quite good results for the Axelsson BTD chest wall velocity predictor V. This was perhaps not surprising for the Weathervane method which was designed explicitly with this in mind. However, it is interesting to note that the (simpler) Axelsson SP and TNO SP methods seem to perform equally well.

Particularly for small charges there was very good agreement between the various methods. For large charges the agreement was good close to the wall and far away from the wall. In an intermediate regime (1-3 BTDs wall distance) we saw that the SP models diverged somewhat. This was traced back to a “phase effect” in the Axelsson mathematical model. The TNO SP method seemed to overestimate the injury in this regime, which was due to a deliberately chosen deviation from the Axelsson model, in order to avoid a possible underestimation of injury, as was observed for the Modified Weathervane SP and Axelsson SP methods.

The results for individual gauges in the Modified Weathervane SP model were also examined and the results were not promising compared with Axelsson BTD. In fact, the reflected pressure assumption for the front sensor was seen to consistently give much too high chest wall velocities (the regular Weathervane will be slightly better here). The assumption of ambient pressure for the rear sensor is incorrect, even without a wall, and the pressure at the side gauges is always lower than the free field pressure. With a wall present, these individual gauge predictions become even worse. However, it is interesting that the errors in general seem to “cancel each other out” so that the total chest wall velocity predictor is reasonable, even with a wall present.

To improve the physics in the (modified) Weathervane model, an option would be to find a different method of calculating for the individual gauges when a wall is present. However, currently this is not thought worth the effort since, for all practical purposes, the available single point models produce good enough results. This has been demonstrated for such a large variety of cases in this paper, that we believe that it is unlikely there will be a relevant case where the models deviate significantly. With the large uncertainty in the Axelsson BTD model itself, developing more advanced models to estimate it more accurately is probably not the way to go.

We have not adressed the topic of whether Axelsson BTD actually gives correct injury predictions, except for the observation that it predicts less lethality than Bass. Our focus was on whether the various simpler SP approaches were able to approximate the Axelsson BTD model. Since the Axelsson BTD method itself must be considered as an approximation method, which has not been validated for any of our case studies, an approximate agreement has been considered as sufficient. When the Axelsson BTD model gives reasonable predictions, either of the SP approaches will usually give acceptable results. For the analysis of a specific scenario, knowledge about how the different SP models behave, should help in assessing the situation. For example, the TNO SP method will most likely give the highest injury estimate and may be preferred for use if one wants to be particularly careful.

## References


(1) Kiran J H, A method for the estimating the fragment characteristics from an IED, Proceedings of the 13th Int. Symposium on the Interaction of the Effects of Munitions with Structures, Brühl, Tyskland, 11-15 May 2009

(2) Kiran J H, Teland J A, Estimating the fragmentation characteristics and penetration effects of an IED, FFI/RAPPORT-2009/00845

(3) Teland J A, Kiran J H, Penetration of highly irregular fragments, Proceedings of the 13th Int. Symposium on the Interaction of the Effects of Munitions with Structures, Brühl, Tyskland, 11-15 May 2009

(4) Bowen IG, Fletcher ER, Richmond DR, Estimate of Man's Tolerance to the Direct Effects of Air Blast, Technical Progress Report, DASA-2113, Defense Atomic Support Agency, Department of Defense,Washington, D. C. October 1968.

(5) Holm K B, Beregning av dødelighet fra luftsjokk, FFI/RAPPORT-2007/01896

(6) Bass C, Rafaels K, Salzar R, 2006, Pulmonary Injury Risk Assessment for Short-duration Blasts. Personal Armour Systems Symposium, 2006, The Royal Armouries, Leeds

(7) Axelsson H, Yelverton JT, 1996, Chest Wall Velocity Predictor of Nonauditory Blast Injury in a Complex Wave Environment, The Journal of Trauma: Injury, Infection, and Critical Care, Vol. 40, No. 3, USA

(8) Stuhmiller JH., Ho KHH, VanderVorst MJ, Dodd KT, Fitzpatrick T, Mayorga M, 1996, A model of blast overpressure injury to the lung, J. Biomechanics, vol. 29, No. 2, pp. 227-234, 1996, Great Britain

(9) Li E, Yoshinaka A, Josey T, 2008, Weathervane: a single point model for blast injury approximations, 20th Symposium on Military Aspects of Blast and Shock, 2008, Oslo, Norway

(10) Hyde DW, 1991, ConWep - Conventional Weapons Effects, US Army Waterways Experimental Station, US Army, 1991

(11) www.ansys.com

(12) van Doormaal JCAM, van der Horst MJ, An approximation of the Axelsson model for quick injury predictions, 21th Symposium on Military Aspects of Blast and Shock, 2010, Jerusalem, Israel

(13) Zeigler H, Teland J A, Svinsås E, Axelssons skademodell implementert som en subrutine i hydrokoden AUTODYN, FFI-Rapport 2008/01628

(14) Teland J A, van Doormaal JCAM, van der Horst MJ, Svinsås E, A single point pressure approach as input for injury models with respect to complex blast loading conditions, Proceedings of 21st International Symposium on Military Aspects of Blast and Shock, Jerusalem, Israel, October 3-8, 2010