Simulation of ATD pelvic response of an under body blast

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ABSTRACT: Full scale under body blast testing are rather complex and cause a lot of variability in data. The complexity and variability of blast testing can be reduced by a well-developed numerical model that can simulate the various aspects of the loading experienced by the occupant. This paper presented the baseline for coupling LS-DYNA and MADYMO to model the pelvic response of an ATD situated inside the CSIR human response test rig (HRTR), subjected to an under body blast. Two configurations, the flat hull and V-hull were modelled for two different charge sizes 1kg and 6kg. Results were compared to experimental data. Flat hull responses were in comparable ranges, however V-hull simulation responses were much lower.

1 INTRODUCTION

Landmines and improvised explosive devices (IEDs) are commonly used against military vehicles causing injuries to the occupants. The timeline of the load response of a typical vehicle subjected to an under body blast (UBB) is shown in Figure 1. The blast wave reaches the vehicle structure approximately 0.1 ms after detonation. Local deformation of the vehicle floor occurs during the first 2 ms and the impulse transfer due to the UBB is complete (Zakrisson et al. 2010, Franklyn et al. 2017).

This timeline of the UBB can be divided into mainly three vehicle response regimes, namely the localised hull response, the internal vehicle dynamics and the global vehicle motions.

The localised hull response is due to the explosion which propels the shockwave and sand ejecta. The second effect is the internal vehicle dynamics, which is the transmission of the hull reaction loads to internal systems. The third is the global vehicle motions, which includes the vehicle translation, secondary projectile impacts and possible rollover (Franklyn et al. 2017). To understand injuries sustained by soldiers under all of the various loading conditions, it is imperative to analyse the impact of each sub-event on soldier injuries.

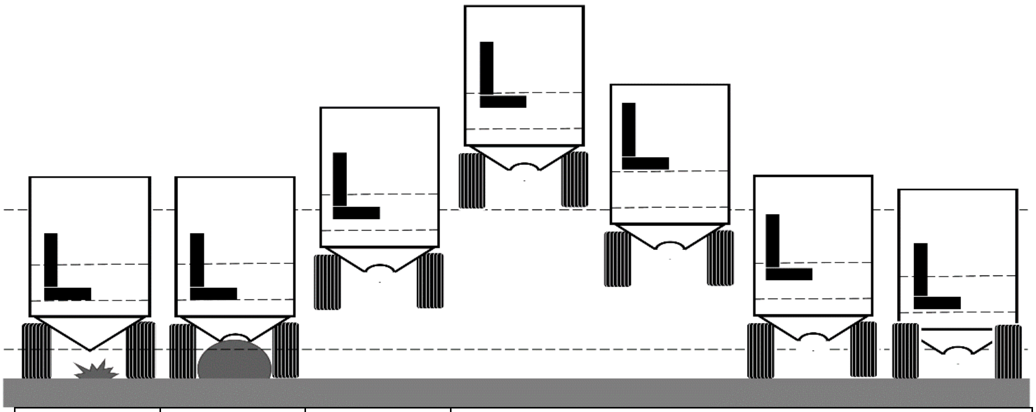
Seats in landmine-protected vehicles have a secondary role of mitigating the resulting forces and accelerations on the occupant following a landmine or IED blast event. An ideal seat must attenuate the load on the occupant and prevent serious injuries (Bosch et al. 2014). This type of research and development relies heavily on modelling and simplified experimental approaches in order to develop and test prototype seating technologies.

1.1 *Modelling vehicles subjected to UBB*

Figure 1 shows that there are several systems and interactions involved in the dynamic response of occupants in military vehicles subjected to a mine blast. All these systems require different techniques for modelling and/or coupling interactions.

Some models look in detail at specific interactions or systems, while others simulate the entire global system by coupling two or three systems and approaches.

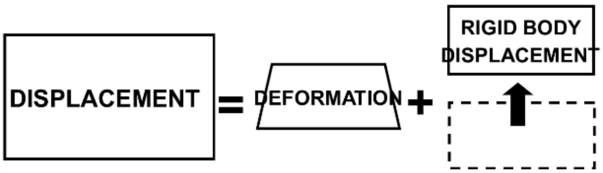
For instance, the blast itself might be modelled using finite element (FE) formulations such as CONWEP, ALE, MM-ALE or user defined impulse loading (Tabatabaei et al. 2012, Schwer et al. 2015), while the global response of the vehicle and the occupant might be modelled using FEM (Finite Element Modelling)



0 ms	0.1 – 3 ms	3 -9 ms	10 – 100 ms			
Explosive detonates	Shock wave hits structure and deforms it	Impulse transfer lifts the vehicle of the ground	Vehicle reaches maximum height	Vehicle start moving downward	Vehicle hits the ground	Tyres / suspension causes some damping

Figure 1. Timeline of an UBB (Zakrisson et al. 2010, Franklyn et al. 2017).

or multi-body dynamics (MBD). The main difference between FEM and MBD approaches are illustrated in Figure 2, with a simple displacement equation at the various stages of a simulation (Renganathan, 2017).



ASSUMPTION	FEM	MBD
BEFORE:	DEFORMABLE BODY	RIGID BODY
DURING:	SHAPE CHANGES	NO SHAPE CHANGES
AFTER:	STRESS, STRAIN & STRAIN RATE	ACCELERATION, VELOCITY & LOADS

Figure 2 Simplified differences between FEM and MBD (Renganathan 2017).

It is evident that the interaction between deformation (usually found using FEM) and rigid body displacement (from MBD) are both important in simulation the displacement of a vehicle and its occupants.

LS-DYNA and MADYMO are commercial simulation codes that respectively utilise FEM and MBD approaches. They can be coupled with the MADCL library, where MADCL ensures that the correct communication protocols are used, and it supports FE data exchange. After each timestep, the nodal displacement and contact surface positions from LS-DYNA are sent to MADYMO, which then calculates the forces acting on these nodes and returns it back (Happee et al. 2003). This coupling is shown in a block diagram in Figure 3.

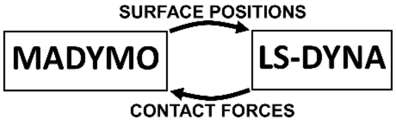


Figure 3. Coupling between LS-DYNA & MADYMO (Happee et al. 2003).

Anthropomorphic test devices (ATDs) are frequently used in vehicle experiments to simulate the response of humans to impact and/or blast loading. It is therefore useful, for validation and design purposes, to model the response of ATDs in simulated blast models as a proxy for the occupant response.

Coupling software like LS-DYNA and MADYMO, provides a robust and fast way to model an armoured vehicle subjected to mine blast and give a prediction of expected injury of its occupants, by utilizing the strength of each of software (Happee et al. 2003).

1.2 *Using a blast capsule*

Rather than performing full-scale vehicle testing, initial experiments are often performed on a blast capsule which is a reusable test platform that re-creates the underside of a vehicle but allows for measurement of important loading and response parameters (such as impulse transfer).

This type of blast capsule also allows for prototype seat testing at reduced cost. LS has designed and built the Human Response Test Rig (HRTR), in which different mine protected seats can be installed on opposite sides, to simulate symmetrical blast comparisons. Occupants can then be exposed to different underbody blast loading conditions.

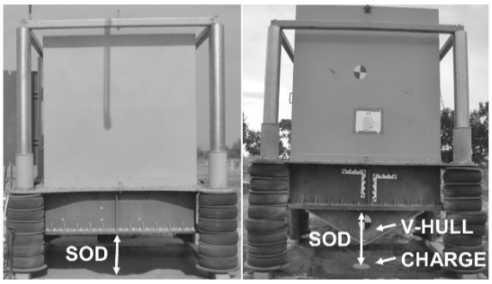


Figure 4. HRTR flat hull and V-hull configurations.

The capsule construction is a combination of steel square tubing and sheet metal, with a V-hull over the length and a total weight of approximately 6 tons with the V-hull. It has four poles attached to a lightweight frame that guides and restricts the capsule to vertical motion. A series of damping elements are positioned at the bottom of the guide poles, to absorb the come-down impact of the capsule. The HRTR currently has two configurations, the V-hull and the flat hull as illustrated in Figure 4. Although cheaper than vehicle testing, it is still time consuming, complicated and costly to perform experiments using the HRTR. Each blast event is unique, although it is more controlled than an actual vehicle test. As the upward (z-axis) accelerations and forces are usually the most significant during an UBB event, limiting global movement of a test capsule in this direction already eliminates a few variables. However, only limited information is available from a blast test on such scale and detail interaction information between the occupant and structures, like the seat pan, become difficult to obtain.

A well-validated simulation model of the HRTR, could improve the understanding of the blast load transfer to the seated occupants, and aid as an additional tool for investigations of detailed interactions. Such a tool will be useful for enhancing the effectiveness of protection technologies, like mitigation seats and PPE. It is also a cost-effective alternative to repeated HRTR testing.

TNO also developed a blast capsule model with LS-DYNA, similar to the V-hull configuration of the CSIR HRTR, to simulate the detonation and test object deformations. This model was coupled with MADYMO for the analysis of the ATD as occupant. The main focus of this study was to understand the local effects of vehicle floor deformation on the lower leg injuries, although pelvis accelerations were shown for one configuration and lumbar forces were not compared. (Kendale et al. 2009, Vlahopoulos et al. 2010)

This paper will provide the details of the LS-DYNA model for the CSIR HRTR, linked to the MADYMO model. The purpose is to compare the pelvis accelerations and lumbar forces to study the effect of the seat on to the spine with the ATD's feet rested on a footrest off the ground and loading only through the seat.

2 MODEL DESCRIPTION

The modelling was done in two parts. The first parts were to subject the HRTR to an UBB, and the second part were to use the seat accelerations from the first part as input parameters into a seat and ATD model in MADYMO, to obtain the ATD pelvic and lumbar responses. Both the HRTR configurations, flat hull and V-hull, were modelled for 2 sizes of TNT, 1 kg and 6 kg.

2.1 *The HRTR blast model*

A quarter symmetry blast capsule subjected to different buried charges, with a stand-off distance (SOD) of 750 mm from the floor, were modelled and reflected around the XZ plane. A Multi Material Arbitrary Lagrangian Eulerian (MM-ALE) Fluid Structure Interaction (FSI) approach was followed using LS-PrePost v4.5.14.

The model consists of three keyword files for the modelling of the air and soil, the capsule, and the combined FSI model, as illustrated in Figure 5.

The first keyword file contained the air, soil and explosive properties, consisting of two parts with 630768 solid elements ranging from 25mm to 200mm and one virtual part the explosive. A node set at Z = -1000 were setup as a "bed of rocks" to prevent the model to "take off" in the negative Z direction.

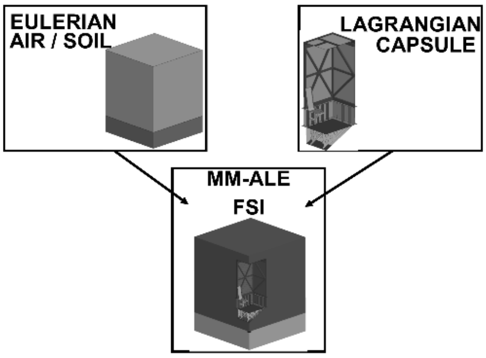


Figure 5. HRTR UBB model layout.

A global constraint was set to only allow movement in the Z axis and restrict movement in the X and Y axis. The air was modelled using the keywords *MAT_NULL and EOS_LINEAR_POLYNOMIAL as an ideal gas, with an initial pressure of one atmosphere (0.1 MPa) (Tabatabaei et al. 2012, Schwer et al. 2015). The TNT parameters for the Jones-Wilkens-Lee (JWL) EOS were obtained from the LLNL Explosives Handbook (Dobratz et al. 1981) and Technical paper (Lee et al. 1973).

The second keyword file contained the capsule properties. Two capsules were modelled. One with the flat hull (21511 shell elements) and one with a V-hull (24062 shell elements). A seat, with a footrest, were connected to the back wall. All parts were modelled as far as possible with 25mm quadratic shell elements. The total mass of the quarter symmetric model for the flat hull was 1181 kg and for the V-hull 1297 kg.

The FSI model consisted of several keywords for defining the boundaries, the constraints, the detonation, the Volume Fraction Geometries (VFG) and all the control and database keyword cards. Two *CONSTRAINED_LAGRANGE_IN_SOLID keyword cards were created, with the slave set as the capsule and the master as the air and soil. Four *ALE_MULTI-MATERIAL_GROUPS were created for the soil, the air outside, the explosive and one for the air inside the capsule. The *INITIAL_VOLUME FRACTION_GEOMETRY keyword card was used to define 4 volume geometries for each of the multi material groups. The model was terminated after 10ms, with increments of 0.02 ms and a time step scale factor of 0.67.

2.2 *The ATD model*

A multibody seat and ATD model was created in MADYMO release R7.7. The Hybrid III 50th percentile ellipsoid multibody ATD version 7.2, instead of a facet ATD model, were used to reduce computational time. The model had 5 system models, namely: The ground, the cabin, the seat, the ATD and the harness. The ground was set as the reference space. The idea was that the model is setup for ease of direct coupling at a later stage. However, for the current setup, only the seat accelerations were used as input for the model with a MOTION.JOINT_ACC card. The software (LS-DYNA and MADYMO) used, did not reside on the same network and thus coupling were not possible. As a result, there was no feedback between the models for the contact forces and surface positions of the multibodies. Instead, both the experimental, as well as the LS-DYNA model seat accelerations, were used as input. The model is shown in Figure 6.

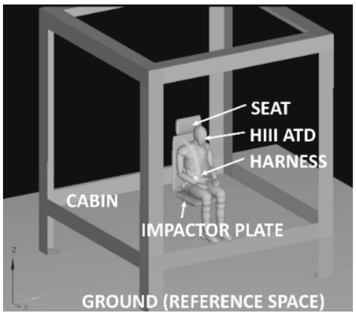


Figure 6. ATD model setup in MADYMO.

3 RESULTS

Comparisons are made for both the structural, as well as the ATD responses in Figure 8. For the structural, the floor and seat accelerations (floor Az and seat Az) of the LS-DYNA simulation are compared to experimental results. For the ATD, the pelvis accelerations (pelvis Az) and lumbar forces (lumbar Fz) results of the MADYMO simulations' seat accelerations (Seat Az), with inputs from the LS-DYNA (SIM 1) and experimental seat accelerations (SIM 2), are compared to the results of the experimental ATD.

A 4 kHz filter were applied to the floor accelerations (Floor Az) of the experimental results. A CFC 1000 filter, with cut off frequency of 1650 Hz, were applied to the seat Az, pelvis Az and lumbar Fz, for both simulations and experimental results.

It must be noted that during the flat floor experiments the floor had an increasing initial deformation as the tests proceeded, resulting in a higher SOD effectively and the floor acceleration for the second test were higher as illustrated in Figure 7.

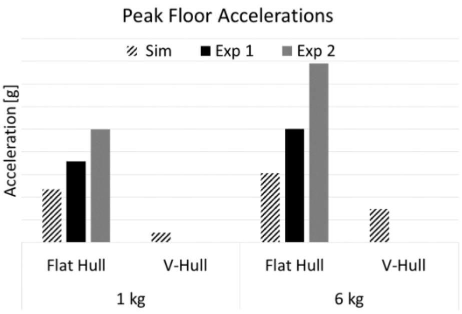


Figure 7. Comparison of peak floor accelerations.

The morphology of the 1 kg and 6 kg flat floor simulation floor Az are similar when compared to the experimental results (Figure 8), however both the simulations have a lower peak value which occurs later than the experimental results (Figure 7).

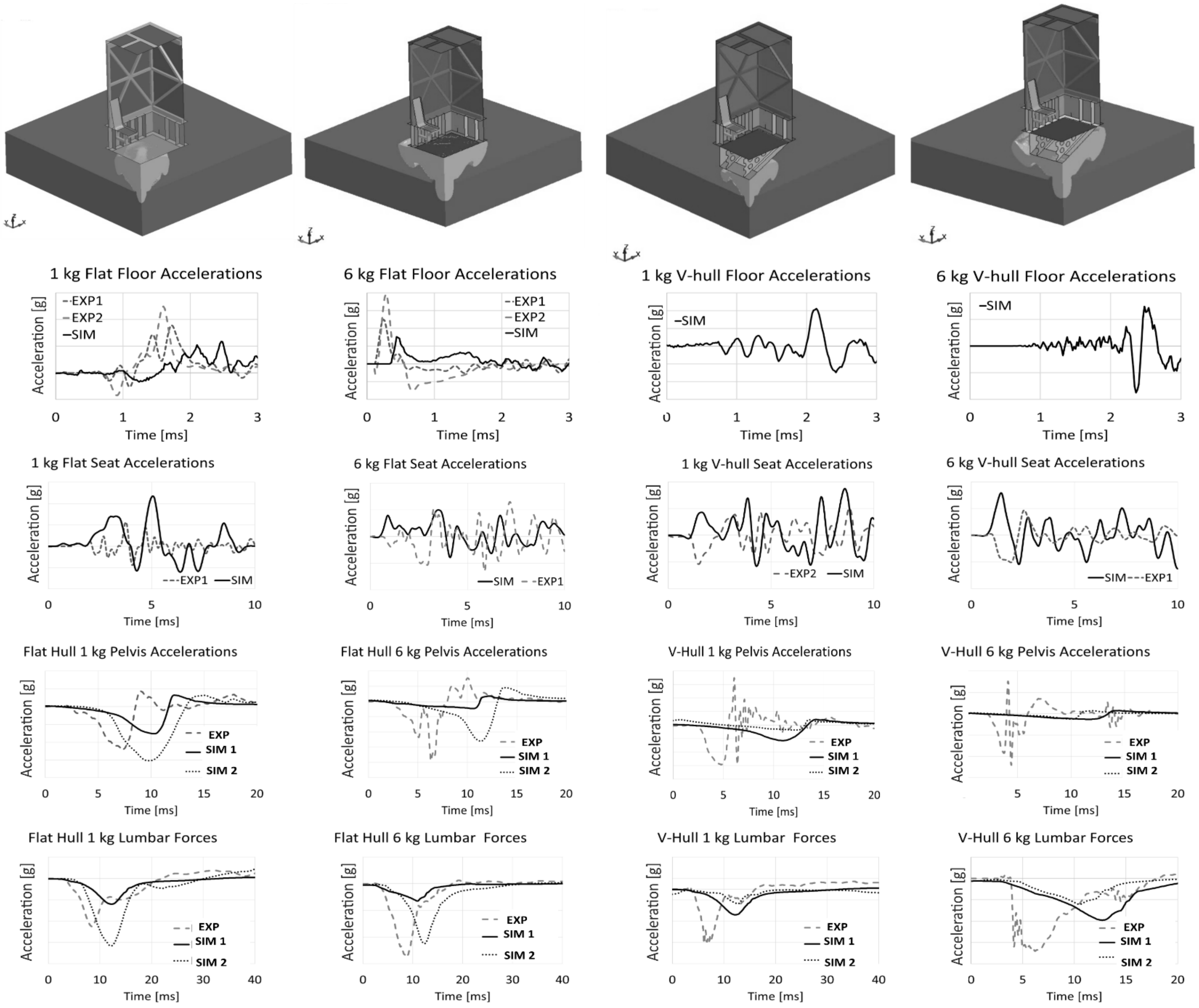


Figure 8. Comparison of floor and seat accelerations of the structure, and pelvis accelerations and lumbar forces of the ATD.

The seat accelerations of the experimental results all had an initial deceleration, however the simulations had an initial acceleration for a similar time period. For the peak 1 kg flat and v-hull and 6 kg v-hull, the simulation seat Az are almost double the experimental values, however for the 6kg flat hull the peak seat accelerations are similar, shown in Figure 9.

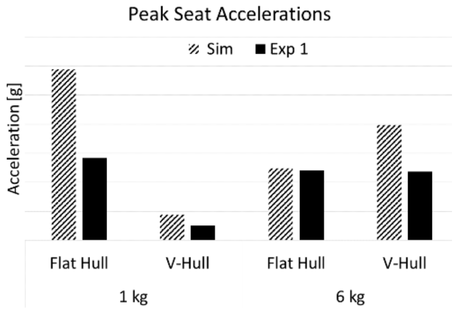


Figure 9. Comparison of peak seat accelerations.

Comparing the ATD pelvis Az, the 1 kg flat hull Sim 1 was 40 % lower and Sim 2 was 20 % higher than the experimental value. For the 1kg V-hull, Sim 1 was 62 % lower and simulation 2 was 86 % lower. Comparing the 6kg pelvis Az, the flat hull Sim 1 was 88 % lower, however Sim 2 was only 33 % lower and for the V-hull, Sim 1 was 89 % lower and Sim 2 was 90 % lower.

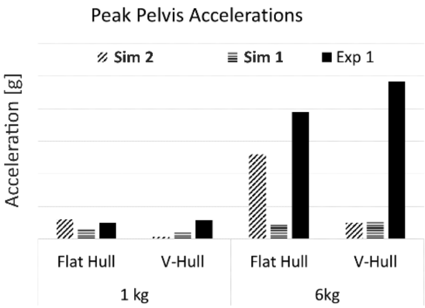


Figure 10. Comparison of peak ATD pelvis accelerations.

Comparing the peak lumbar Fz, the flat hull 1 kg Sim 1 was 46% lower and Sim 2 was 41% higher. For the V-hull Sim 1 was 120% higher and Sim 2 only 26% higher. For the 6kg flat hull the Sim 1 was 76% lower and Sim 2 was 18 % lower. For the 6 kg V-hull, Sim 1 was 42 % and Simulation 2 was 64 % lower.

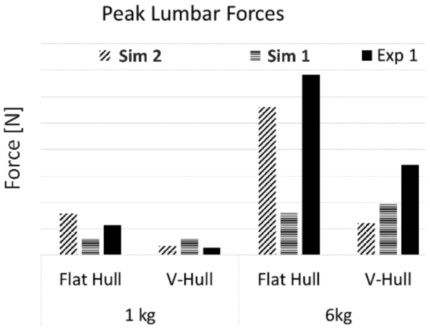


Figure 11. Comparison of peak ATD lumbar forces.

4 CONCULSION AND RECOMMENDATIONS

An Under Body Blast (UBB) of the CSIR HRTR was modelled in LS-DYNA and linked to MADYMO for ATD responses. Both Experimental, as well as simulation seat accelerations were used as inputs into the MADYMO model. The ATD pelvis accelerations and lumbar forces were compared to experimental results. ATD responses were in comparable ranges for the flat hull, however responses of the V-hull were much lower for the simulation results. Models were not coupled and as result, there were no feedback between the models for the contact forces and surface positions of the multibodies, which could explain the difference. The ATD model was also only an ellipsoid model and not a full facet ATD for increased computational speed. It is recommended that more experimental data sets are obtained. It is also suggested to measure strain and displacement of the floor and seat, in addition to accelerations. It is further recommended to improve the material properties for the soil and capsule structure. Coupling the LS-DYNA and MADYMO models will also ensure feedback between contact forces and surface positions.

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