COMPARISON OF COMPUTER HUMANOID SIMULATION AND PRACTICAL FORENSIC PEDESTRIAN DUMMY TESTING

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ABSTRACT

Various successful biofidelic simulations of vehicle-pedestrian collisions exist for research and design purposes, but are impractical for routine accident investigation and reconstruction. Reconstructions with a full pedestrian crash dummy and a representative vehicle have always been problematic because robust and representative dummies are expensive, and need replacement components after tests if they are as fragile as the human frame. This is not an issue below injury thresholds, but such cases are rarely of forensic interest. Many reconstructions have nevertheless used crash dummies to establish impact speeds by correlating vehicle damage location and extent, and the throw distance, but this can be a circular process subject to low biofidelity and systematic errors.

An alternative is to use expendable, simplified dummies in reconstruction exercises. This paper uses results from similar impact configurations of earlier humanoid computer simulations and from separate testing of a dummy developed for police reconstructions in the expectation of guiding further application of the simplified dummy method.

Correlation of the kinematics up to dummy/vehicle separation between the computer simulations and the dummy tests was close enough to provide some confidence based on the limited materials available for study. Initial contact, timing, contact locations and motions of the dummy parts not contacting the car corresponded with little variation due to differences between the simulation and test impact initial velocities. Pedestrian posture, point of impact and vehicle specification aligned well, as did braking and pitch of the vehicle during impact, previously shown to have a material influence on the trajectory of the pedestrian and by implication the throw distance, in addition to the other configuration parameters. The results are therefore confined to the configuration used for this analysis and further work would be needed to generalise the findings for other vehicle shapes, speeds and contact points, pedestrian stature and posture.

INTRODUCTION

Collisions involving a vehicle with a pedestrian or cyclist often differ considerably from collisions between two vehicles or a vehicle and the infrastructure in forensic terms. In the latter instances the evidence available at the scene and later is usually more durable and pronounced: debris, vehicle and property damage, besides marking of the roads before or after impact indicate directions and speeds, even if there are no injuries to the occupants. It can be easier to access the evidence both on attending the collision and later by re-visiting the location and following up the vehicle in the insurance compound or repair shop. In contrast, a pedestrian may be thrown well away from the initial impact location in a direction dependent on the shape of the vehicle, and may sustain multiple injuries from the surroundings as well the vehicle; they may be moved to safety by first responders or even taken to hospital well before investigators can attend. Typically, the vehicle will have continued moving some distance after the initial impact, and in some cases may not even stop at the scene. Often it is parked out of the way of other traffic, and traces on the road surface of initial impact with the victim may be minor scuffing of the surface and a little debris, easily affected by passing traffic or people attending the scene. With increasing fitment of enhanced brake systems, tyre marks on the road may be difficult to detect and attribute. Impact locations on the vehicle can difficult to identify, especially on hard points that do not dent easily, or on soft parts that recover shape. Scuff marks, clothing fibres, hair, skin and blood on a dry vehicle can all be missed on cursory inspection and be invisible if it is wet, or removed by subsequent precipitation or deliberately. In one minor injury case vehicle body repairs had been completed in all innocence after police had completed their on-scene inspections and before a research team visited the driver within 24 hours of the incident. [Hill et al, 4] Eye witness, driver and victim statements are a poor substitute, at best only corroborating hard evidence.

Not only do these factors give room for doubt or dispute in cases where fault needs to be established, it is frustrating to have inadequate information for research which is directed at injury mitigation by design of vehicle systems and more importantly at detecting pedestrians in order to avoid collisions if possible. The more thoroughly a case can be reproduced, the easier and more certain the creation of effective countermeasures will be.

Historically, cases have been replicated using the best available information from the scene of a collision, a car of the same type and a standard crash test dummy or Anthropomorphic Test Device (ATD) adapted for a standing posture or supported in a walking or running posture as indicated by the case information. The car is then propelled into the dummy in the estimated configuration of the case. The test results in terms of contact locations on the dummy and the car, and the ground, damage to the car, braking distance, and final locations of dummy and car are then compared, often with repeat tests with adjusted initial conditions until the best match between test and field data is achieved. Such testing provides the basis for forensic judgment of impact velocity from throw distance, usually needing other supporting evidence to obtain conviction of an at-fault driver in court.

Apart from the cost of performing such repeated impact tests with a vehicle restored to damage-free condition between tests, and the risk to the test driver, etc., the dummies were usually adaptations of those designed for car occupant surrogation with modifications to allow a stable upright posture and did not represent the relevant strengths, stiffness, ranges of motion and injury-sensing of a human. Further difficulties in having sufficiently robust instrumentation to withstand impact especially with the ground, and integrity of data transfer by cable, wireless, or internal recording restricted the scope of information that could be obtained. It is therefore questionable whether some of the early tests were representative enough to generalize throw distances as indications of vehicle speed from relatively few experiments. In turn, the parameters for reconstructions and for subsystem tests replicating the vehicle damage from real-world cases using a stand-alone headform or legform impactors relied on those experiments and form the basis of all current regulations, despite the impactors being mechanically unlike the human body parts. Nevertheless, in the absence of better data and tools, the social imperative to reduce fatalities and lesser injuries obliged the best available means at the time to be applied in legislation.

These were motivations behind the pedestrian protection research initiated at Jaguar Cars and conducted by Ford Forschungszentrum Aachen GmbH (FFA) using component impact testing, computer simulation [Howard et al, 1, 2] and On The Scene Accident Investigation [Morris et al, 3] which was the pilot to the ‘On the Spot’ research [Hill et al, 4] and the later IMPAIR study in Berlin and Mecklenburg-Vorpommern [Koch & Howard, 5].

Independently, within the Metropolitan Police (London, UK), an interest arose recently in more robust evidence in pedestrian cases. This led to development of a repeatable low-cost, disposable pedestrian dummy with which to reconstruct collisions including the trajectory of a pedestrian as captured on CCTV. This work is unpublished but demonstrations using several examples of the dummy were staged at the 2013 and 2016 Institute of Traffic Accident Investigators' (ITAI) Crash Test Days [ITAI, 6,7]. (see fig. 2) Among the staged impacts by coincidence there was one with the same vehicle model and pedestrian configuration as simulated during FFA research.

Figure 1. Low-cost pedestrian dummies - 40 kg child, 80 kg adult

The opportunity has therefore been taken to compare the impact behaviour of the dummy and vehicle with the simulations. For this purpose, our own records, normal and high-speed video published by The Institute of Traffic Accident Investigators [ITAI, 6a, 6b] on DVD and FFA's published materials were accessed by kind permission. It later transpired that the DVD formats were unsuitable for detailed analysis and ITAI arranged for the high speed video to be made available in the original format.

This paper reports on these comparisons, their limitations, and because perfection has not yet been achieved, comments on implications for further work.

COMPUTER SIMULATION

Background

Howard initiated research into pedestrian safety at Jaguar Cars Ltd. to gain better understanding of design requirements for injury mitigation in the real world, and to contribute to evolution of regulations and test methods. The latter were partly based on work by Ashton and McKay [9] but vehicle shapes had subsequently changed in the interests of fuel economy and there was debate over the validity for the contemporary vehicle parc of the European Enhanced Vehicle-Safety Committee [EEVC, 10] tests on which the European Commission's legislative proposals were being based.

Howard and Thomas [2] coordinated test rigs, test impactors, vehicle countermeasures, [for example Cady et al, 11] and determined that detailed on-the-scene in-depth accident study was also required to support updating of EEVC pre-regulatory research.

This work later proceeded under the aegis of Ford Forschungszentrum Aachen GmbH to creation of a computer model of pedestrians and vehicles with a number of objectives in view, and to funding the On-the-Scene Accident Investigation (OTSAI) project in Nottingham [Morris et al, 3], the pilot to the On-the-Spot project [Hill et al, 4].

The principal objectives of the simulation were firstly to be able to represent any pedestrian in terms of stature, mass, body proportions and age, whether a generic case, or to reconstruct a specific individual for case reconstruction, and secondly to represent injury mechanisms with sufficient biofidelity to reproduce real world collisions and apply the results to study potential mitigation in vehicle design. This would be addressed by use of the GEBOD database for prospective simulations, and clinical anthropometric measurements for reconstructions.

Those objectives were augmented by the field research, a joint effort lead by Loughborough University's vehicle Safety Research Centre, in conjunction with Nottinghamshire's Constabulary, Queen's Medical Centre hospital, Ambulance Service, Fire Service and Highways Engineer's departments. OTSAI was established to provide enough information on pedestrian, vehicle and driver behaviour leading up to collisions to inform the specification of pedestrian detection and warning systems, control strategies for collision avoidance systems and active injury mitigation systems such as deployable body systems (pop-up-hoods/bonnets or external airbags). The real world data was also of value for all participants in trialing additional collision investigation techniques, such as video recording of the scene on arrival, location, condition and treatment of victims, damage and other visible evidence, traffic conditions whether affected by the incident or not, weather and lighting conditions. Vehicle damage and other evidence is often easier to comprehend from video than from still photography alone. After clearance of the scene and before reopening to normal traffic, the police could make a first-estimation of the case vehicle approach, speed and path through the impact, again recorded on video, including sight lines. In addition to all the usual measurements, witness statements photos and UK police STATS19 forms details, careful analysis of the video is capable of revealing information captured but not specifically selected at the scene, providing useful corroboration or critiquing of conventional data. Information collected at the scene, including during the pilot project by a trauma medic in the team, was combined with information gathered at the hospital casualty department by the trauma specialist attached to the project team, under the relevant ethical protocols.

Model Description

To give sufficient biofidelity and allow critical bone stresses to be determined by the simulation, Finite element (FE) models were developed using the LS-DYNA FEM code, and included 6 year-old child, 5th percentile adult female, and 95th percentile male, aligned with the standard Hybrid series of vehicle occupant dummies, together with the H-IIIP 50th percentile adult male pedestrian dummy which has a pelvis modified to adopt a standing posture.

The basic model was progressively developed using human data to represent more closely the geometry and material properties starting with the legs and neck,. The technique developed for Ford by Hardy et al at Cranfield allowed for scaling to also represent ethnically differentiated physical proportions, or a specific individual person [Hardy et al, 10]. Care was taken to cater for representation of fracture, particularly in the long bones of the leg, it having been confirmed during OTSAI that trajectories could be changed considerably in the real world depending on articulations due to fractures, especially away from the knee and hips. The resulting "humanoid" 50th percentile adult male models (AM50) provided the templates for the rest of the humanoid family. (see figure 2) It was also envisaged that more detailed models of relevant parts of the pedestrian could be inserted during certain stages of the collision simulation to examine, for instance, rib, shoulder or brain trauma at the time of contact, or violent rotation during throw thereafter – including ground contacts. This would avoid extensive use of computer resources during the parts of the simulation where a detailed model would not make a useful contribution, such as while the relevant body regions were not in contact with the ground or vehicle and not subject to high accelerations. These models preceded and are completely independent of the LS-DYNA "Hybrid III 50th Percentile Male Standing" model which is currently in beta-test phase [11].

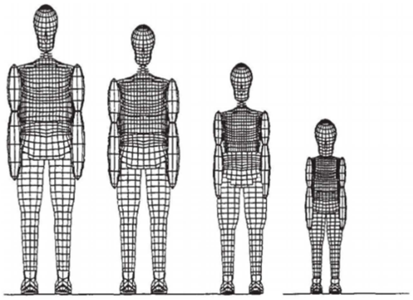

Figure 2. Humanoid models - 95th male, 50th male 5th female percentiles and 6 -year old child

In parallel, a computer model of a Ford Focus Mk.I was developed with a highly detailed front end. All the vehicle components interacting with a pedestrian used material data validated by sub-system tests and impactors representing the pedestrian, [Philipps & Friesen 12, Howard et al 13]. The pedestrian posture at impact, location relative to the vehicle front, the vehicle velocity and attitude, including braking and brake dive can be adjusted in the initial conditions.(see figure 3).

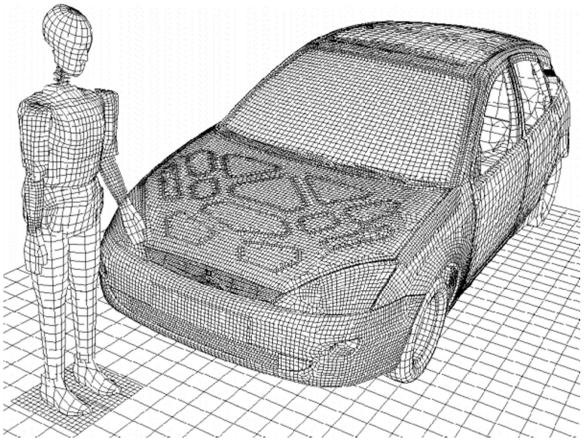

Figure 3. Humanoid AM50 Pedestrian and detailed Ford Focus Mk.1 FE models

The total model capability was planned and used so that a large parametric design-of-experiments matrix was employed to generate conclusions once the AM50 humanoid model had been validated and thus allowed one case to be identified for comparison with the low-cost dummy test in the present paper.

Model Performance

The humanoid model was validated against existing results of pedestrian collision tests with adult male cadavers, and replicating the vehicle parameters reported from those tests [Ishikawa et al, 14] at 25 km/h and 39 km/h, and the exercise yielded some improvements to the humanoid model as a result of the initial simulations, including positioning of the arm to avoid interference with pelvis contact, and in modelling of tibia fracture. Details are given in Howard [5], and results showed better correlation with the cadaver tests of leg trajectory, head velocity, and by a factor of 10 with head impact location. These capabilities were of particular importance for the subsequent research into effects of pedestrian orientation, posture, and alignment, vehicle shape, local stiffness, velocity, braking, and pitch due to braking, for vehicle design guidance, and ideal for the comparisons below. The model was then further developed, the shoulder being a major challenge. Versions were also developed for research into cyclist and motorcyclist collisions with vehicles [McLundie, 15, Watson, 16]

APPLICATION OF TEST DUMMIES TO PEDESTRIAN RESEARCH AND FIELD INVESTIGATION

Background

The simulation of vehicle-to-pedestrian collisions has been conducted for many years, originally using military dummies such as the RAE dummy intended for ballast or in rescue, parachute and ejector seat tests [Guignard, 17], or for automotive occupant tests and were fundamentally designed to represent average adult males in terms of dimensions, masses and articulation angles, perhaps with provision for instrumentation and joint stiffness, but most of all for durability in repeated use. Alderson’s VIP was modified to serve as a standing pedestrian dummy, as was his Sierra “Stan” dummy.

Figure 4. Demonstration of BL 1300 Pedestrian Safety car with catcher, TRL, 1974
(abergraffic)

TRL demonstrated pedestrian “catcher” devices using a suspended dummy in 1974 during the 5th ESV Conference, [Jehu, 18] (see figure 4), and more recently the OPAT Pedestrian dummy in research on energy absorbing surfaces and external airbags [Holding et al, 19]. The - APROD (Association Peugeot-Renault Omni Directional) automotive dummy, developed for side impact with improved thorax shoulder lateral biofidelity was also adapted for pedestrian testing [Brun-Cassan et al, 20; Suthurst and Hardy, 21].

One of the most completely developed pedestrian dummies is the Honda / GESAC POLAR 2 [Huang, et al, 22; Fredriksson, et al, 23; Crandall et al, 24] which have the combinations of biofidelity, robustness, telemetry etc. suitable for simulating collisions up to 50 km/h, with sophisticated knee joints in particular [Artis et al, 25]. Once again, the design is based on an occupant dummy, in this case THOR, therefore inheriting improved thoracic characteristics. A very different approach was used to mimic human optical, thermal, and radar signatures for pedestrian sensing system research in a resilient form in case the test failed [Moxey et al, 26].

Elsewhere a number of reconstructions of specific accidents have been performed using Hybrid IIP dummies, now superseded by the Hybrid IIIP with improved bio fidelity [Humanetics, 27], but with replaceable steel tubular leg segments, increased robustness, knee, hip and spinal, joints and flesh, adapted to enable free-standing on both feet including a partially raised foot, for greater flexibility in setting more realistic postures. Such standard dummies typically cost US $80,000 to $90,000 and replacement tibia sections and associated parts around US $1,000, apart from calibration equipment. Specialist dummies may cost three times as much.

Dependency of trajectory on test dummies

It was long recognised that the critical non-fatal injuries to pedestrians involved lateral impact to the knee, and to some extent the pelvis, so attention is typically paid to simulating lateral impacts in specifically pedestrian dummies, and therefore to the design of the knee and hip joints for that mode. Howard [1, 28], investigated many configurations of impact and the resulting trajectories. On impacting the pedestrian's leg, the response is governed, besides the vehicle velocity, by the orientation relative to the vehicle.

When facing away from the vehicle, the knee bends most easily, promoting a sitting posture as the upper and lower leg are propelled from under the torso before that in turn rotates backwards with the shoulders and head typically impacting the windscreen area, and then translates with the vehicle to a greater or lesser degree, depending on the pedestrian stature and the vehicle shape.

When erect and facing towards the vehicle, the knee and hips have a limited range of motion in the direction of the vehicle, so the legs are less able to rotate relative to the torso and the mass of the legs and torso impose higher inertia and hence more damaging forces at the point of contact, and typically causes more rotation and higher impact velocity of the front of the head, again depending on the pedestrian stature and the vehicle shape.

When the impact is lateral to the pedestrian, the closest knee is unable to rotate freely, but the hip is less restricted than in the last case and interaction with the other leg may increase the loading on the impacted knee. The legs may therefore rotate from under the torso to some extent, resulting in a motion between the other two cases. As the torso rotates down onto the vehicle in this case, the shoulder and possibly the elbow make contact before the head, which then rotates more violently, potentially increasing its impact velocity, both effects increasing risk of brain injury. Another effect of this sequence can be that available deformation of the bonnet in which energy can be absorbed in head impact may already been reduced by the shoulder impact, although whether the head velocity has been reduced thereby is highly dependent on many detail variables in the pedestrian and vehicle configurations. Yet again, overall motion depends on the pedestrian stature and the vehicle shape, including the shape across the vehicle in plan.

Further complications arise from the pedestrian's posture: if the feet are not alongside each other, or if the pedestrian is facing other than perpendicular or parallel to the vehicle longitudinal axis, the pedestrian will be subjected to a torque about the vertical axis and will have a yaw component added to the trajectory.

In a walking or running action, with only one foot on the ground, the motion will yet again be affected, in addition to the momentum transverse to the vehicle which may bring the torso and head into contact with laterally spaced locations on the vehicle, as also if the vehicle is turning sharply or in a spin.

Given such variability, it is essential that as much useful information as possible is obtained from the scene of a collision, from the damage and marking on the vehicle, and from all the injuries inflicted on the pedestrian, not just the most serious. In a number of cases, pre-existing damage on the vehicle, and in the majority of serious cases injury caused by contact with the road environment, and/or further impact with the primary or a secondary vehicle must be identified and eliminated from consideration of the initial throw trajectory reconstruction.

In most cases maintaining the posture of the pedestrian dummy pending impact has involved either standing it on both feet with the ankle, knee and hip joints tightened to ensure stability which may then restrict dynamic responses during the impact event, or suspending the dummy in a sometimes unnatural dangling posture. In other work, a supporting structure has been used. In most cases care has been taken to ensure release just before or immediately on impact so that the motion thereafter is uninhibited by extraneous loads. For many years any need for data from the dummy involved a data cable which was vulnerable to snagging and damage, and could also affect the trajectory, but these problems are now circumvented by robust telemetry.

Such considerations are evident in the literature, advising caution in applying throw equations to an investigation to determine impact speed, [for example, Otte, 29; Bhalla et al, 30; Happer et al, 31], particularly when the speed range and impact configuration depart significantly from the data against which the equations have been validated. The derivation of throw distance, injury, damage, impact velocity, dummy biofidelity, etc., is inter-dependent and a somewhat iterative process.

Before the advent of high quality continuous CCTV and traffic camera recordings that capture usable, accurate video footage, and potentially electronic data records from active pyrotechnic pedestrian protective device control units, some of the conclusions were unavoidably reliant on one or more intelligent assumptions.

Alternative approaches. There is a major category of pedestrian ATDs which only represent parts of the anatomy of a pedestrian, thereby allowing subsystem experiments with vehicles without the careful set-up and inherent variability of trajectories associated with full dummies. The most widely encountered of these other devices are the leg, upper leg, child head and adult head impactors developed initially by the EEVC [10], then were adopted by EuroNCAP [27] and the EU for the Directive on the Protection of Vulnerable Road Users [33], and later by other administrations before incorporation in UN ECE Regulations [29] and several other NCAP protocols. Although controversial in some aspects of biofidelity during development, these impactors allow considerable mechanical robustness, repeatability, and economy suitable for development of injury mitigation through vehicle design measures. The FlexPLI (ref) was developed by JARI to overcome some of the shortcomings of the above leg impactors by mimicking bending of the femur and tibia without reaching fracture, in addition to improved knee behaviour, and is being phased in by EuroNCAP, EU and UN ECE.

A further development, proposed in conjunction with Howard and Thomas's programme, but apparently not fully pursued anywhere, was to use bio-mechanically accurate, expendable physical models, for critical anatomical regions, using simulated bones [Sawbones, 35; Eckstein et al, 36], organs and flesh [Kyle & Murray, 37], intended for realistic training of surgeons. The prime candidates for pedestrian crash dummies would be the femoral and tibial segments.

A possibly unique development was the Rotational Symmetrical Pedestrian Dummy developed by INRETS and Chalmers Techniska Högskola [Cesari et al, 38]. This aimed to avoid the unpredictable dynamics of limbs and orientation to assist parametric experiments or generic accident reconstruction, and was particularly applied to bumper design and contact areas for the pelvis, upper body, and head. As its name suggests, it comprised a single vertical sequence of cylindrical metal segments covered in graduated foam to simulate the bone, flesh and internal organs, with single joints representing both the knees, both the hips, neck, etc,

Finally, the BD pedestrian dummy has been developed to reproduce damage to the vehicle that is realistic and robust with replaceable parts, and a mostly wooden skeletal structure that looks more human-like than typical automotive dummies. Tendons can be tightened and a one-piece neoprene suit is fitted over all the other substitute tissues. [Weyde et al, 39]

In every case, the dummies share one or more of the disadvantages concerning cost, robustness, biofidelity, applicability, availability, or repeatability. The majority of dummies must be re-calibrated before use and after a defined time or number of tests, involving availability and expense. Despite this, they each have advantages in one or more areas.

A Practical Forensic Pedestrian Dummy

There is clearly a space for a practical, low cost, readily available dummy – or indeed a range of dummies, for forensic reconstruction of serious or fatal collisions, where the depth of study is justifiable, but budgets are limited. Given these circumstances, it is surprising that more attention has not been directed to this issue, unless the urgency of particular cases is in conflict with constructing a meaningful research program and the unique nature of cases where existing methods are not conclusive does not promise a return on the investment in such a programme.

While much of the research, and indeed the resulting legislation, has been directed at the largest proportion of real-world serious and fatal injury-accidents, which occur at urban areas at speeds around 40 km/h (24 mile/h), police investigations often involve cases of excessive speeds in urban environments, hence the forensic capability has to be correspondingly higher and therefore problematic for conventional dummies. The author is able to give limited details of an exception, which by coincidence had a number of close parallels to the Ford computer simulation projects, in that a Ford Focus Mk.1 was available from police resources and used for demonstration rather than a specific reconstruction. As there had been no joint planning, there were some minor differences in the test specifications, but also a large one: the impact velocity.

Prompted by a disputed serious car to pedestrian collision within London's Metropolitan Police area, a reconstruction dummy was developed over three phases, and tested at the College of Policing's Hendon site by Inspector Richard Auty. At the third iteration it was assessed as satisfactory by an independent external expert against a range of relevant requirements.

The dummies were constructed by Ultimate Proof, with correct segment dimensions to represent the pedestrian in the case (table 1, generally using wood, articulated with simply hinged joints. The limbs are pre-tensioned by continuous chains connecting the extremities to the thorax, thereby allowing adjustment of the posture. The thorax itself is filled with a granular ballast, thereby simulating the internal organs' mass and mobility to a certain extent. The head is moulded in a rigid dense material to the required size and mass, and is connected by a chain to the thorax, passing through a stiff rubber washer so that the chain tension can be adjusted to set the head posture.

The cost of each dummy is in the range of GBP600–700 (around EUR900 or USD1000), a fraction of the cost of conventional dummies.
At the stage of development at the tests addressed here, the hip movement was restricted so as to maintain standing posture, but has since been upgraded. Also subsequently, a number of adult and child dummies have been produced (see table 1 and figure 1) and demonstrated in various tests including as cyclists.

Table 1.
Main Specification 50%AM FE model (Howard) and Test Dummy (Ultimate Proof)

Parameter	FE Model	Dummy
Total Mass (kg)	78.15	78.0
Overall Height (m)	1.75	1.75

Simulations and Tests

The sources for the test information, pre- and post-test photographs, standard and high speed video recordings are the ITAI Crash Day at Bruntingthorpe Airfield, Leicestershire, UK in June 2013 [6, 7, 8]. The ITAI is a professional body with a membership of current police, and retired police, research, and other traffic collision investigators. The purpose of the event is to stage crashes in an otherwise safe environment that is neither a public road nor a crash laboratory, for training, continual professional development and research. A variety of drivable used vehicles from various sources are selected according to expressed needs or themes of each event. Tests may be devised to provide insights that are not available from mainstream laboratory certification and consumer-rating testing, for example lower or much higher speeds, different target vehicle orientations, or special vehicles such as an ambulance.
Preparation typically involves, remote-control steering, speed and braking control, and marking up for film analysis. The vehicles are run under their own power for a considerable distance for the seed to stabilize, accompanied by a control and/or chase car(s) to ensure safe abort in the event of a failure or when the vehicle under test continues to run after impact. For the pedestrian and cyclist tests, the vehicle may be fitted with a protective grid and driven normally by an onboard human with a full-face crash helmet.

Records of the impacts are made using standard and high-speed video at various trackside locations and, in some cases, onboard cameras, and stop-frame cameras. Still and video cameras are used to record the vehicles before and after the tests. Instrumentation comprises standard police-issue hand-held radar detectors, and some onboard instrumentation such as accelerometers and original equipment electronic data recorders where fitted. Specific equipment may be involved for some tests particular purposes such as different technologies of speedometers to compare actual speed, and post-crash 'frozen' indications.

Six of the tests [see table 2] on the event covered here included pedestrian dummy impacts. As can be seen, there is one case that is very similar to a case simulated much earlier by Howard [2]. However, the possibility of making the comparisons in this paper was only recognised during the event, and as has been mentioned, no prior coordination was possible.

Table 2.
Test conditions

Test no.	Vehicle	Dummy	Impact (km/h)	Throw (m)
2	Ford Focus	Child	76	<1.0
2a	Ford Focus	Child	76	25.5
4	Ford Focus	Adult	55	18.5
5	Toyota Avensis	Adult	55	25.1
8	Toyota Avensis	Child	84	36.0
10	Ford Mondeo	Adult	72	36.7

Table 3.
Ford Focus/AM50 computer simulation conditions

Offset 0.5 m	Impact Velocity	Brake pitch	Deceleration
Sim. no.	Km/h	mm	g
B08	25	0.0	0.0
B04	25	0.0	1.0
B12	25	-70	1.0
B06	40	0.0	0.0
B02	40	0.0	1.0
B10	40	-70	1.0

RESULTS

Computer Simulation

Existing results for the Ford computer models [1, 2, 10, 12, 13] have been used. The closest comparison is between test number 4 and simulation B10, both have the adult dummy standing with feet in line with each other, facing the left side of the vehicle pathway and struck by the Ford Focus near its left side while diving under heavy braking, albeit at an impact speed of 54.7 km/h (34 mile/h) in the test and 40 km/h in the computer simulation.

The level of detail in the computer model precludes simulation of the complete pedestrian trajectory within the resources available for the comprehensive research programme. Once interaction between the vehicle and the humanoid has ceased, the motion in most cases does not need representation of the vehicle, nor the internal detail of the pedestrian, and a MADYMO model could take the final FEM positions and velocities of the body segments as initial conditions to simulate the rest of the trajectory

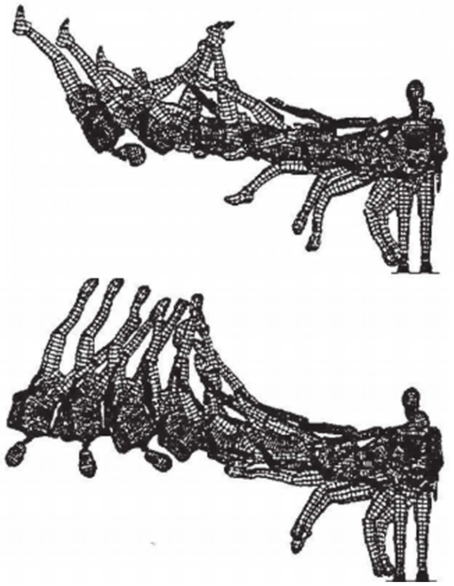

Figure 5. Effect of -70 mm brake pitch: impact velocity 40 km/h, vehicle deceleration 1.0g: top no pitch; bottom with pitch

Howard [2] compared the effects of different locations of the pedestrian across the front of the vehicle, different postures, impact speeds, and the effects of brake pitch and deceleration. Of interest here is the effect of pitch at an offset of 500mm with and without pitch (see figure 5). Brake dive leads to less rotation of the pedestrian about its vertical axis and more about its fore-aft axis, implying more rotational energy transferred due to the lower leg contacts; longer throw distances were also predicted with pitch than without.

Four representative simulation outputs for case B10 at 0.05 second intervals show the main stages of the impact sequence (see figure 6).

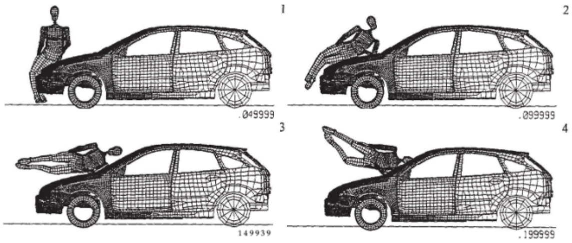

Figure 6. Simulation of Ford Focus transverse impact with standing AM50 humanoid offset 500mm at 40 km/h with 1g deceleration and 70mm brake dive

Firstly the knee has rotated outwards allowing the tibia and femur to wrap over the front; at 0.10 sec. lower leg has lost contact, the vehicle has slid beneath the femur, the pelvis is in contact with the bonnet and the elbow has contacted the rear of the bonnet and near the cowl area; by 0.15 sec. only the thorax via the upper arm is in contact with the vehicle; finally, the head strikes close to the A-pillar about midway up the windscreen.

Physical Test

The results published by the ITAI on DVD comprise standard and high-speed video played back at standard speed as well as time-lapse stills, pre-test and post-test photos of the vehicle and laser scans of the vehicle and complete crash scene, the last item shows the initial and final positions of the dummy and the rest position of the vehicle, confirming the throw distance as 18.5m. The speed of impact was 34 mile/h (54.7 km/h, 15.2 m/s), 37.5% higher than the 40 km/h of the simulation.

The available data does not quote an actual offset, and it is difficult to differentiate the bumper-to-leg impact location for the child and adult pedestrian dummies from photographs, but they appear to be between 600 and 680mm from the centerline.

The DVD format had a number of drawbacks for analysis, so access to the original high speed video file was generously made available. The DVD screen aspect ratios and nominal frame rates differ from the original video, and adapting a nominal 30 fps to 25 fps by normal DVD production methods involves rejection of some frames and appears in video editing software to duplicate others, not necessarily in the correct sequence. Although the sequencing and duplicated frames can be rectified, the missing frames could not, and interpolating stochastic events is unsatisfactory.

Using techniques developed by the author for high-speed video from crash laboratory tests with airbags, the main features of the dummy and the vehicle have been (see figure 7). Note that the profile shown extracted of the vehicle front is not the side view outline, but is a close approximation to the profile at the lateral coordinate of the estimated point of initial contact with the dummy leg.

Figure 7. High Speed Video frame showing extracted features of impact of Ford Focus into Ultimate Proof dummy

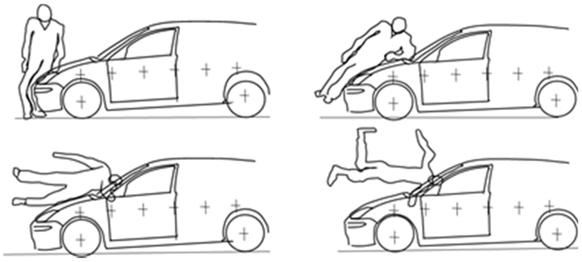

Figure 8. Physical test of Ford Focus transverse impact with standing Ultimate Proof dummy at 40 km/h with 1g deceleration and 70mm brake dive

The timing of the main contact events (see figure 8) was calculated using the nominal frame rate of 1,000 fps replayed at 29.95 fps. The pelvis contact shown in figure x4 takes place at 0.019 s after initial lower leg contact, whereas the simulation contact takes place at 0.050. The remaining frames shown all are calculated as even quicker than the simulation for reasons yet to be identified. It was noted that the vehicle had fully pitched due to braking before it entered the video frame, the rear wheels rotated in contact with the ground throughout, but that the front wheels only locked as the dummy finally lost contact (head to windscreen) and launched into the final trajectory. At the same time, the vehicle pitch reduced. The vehicle continued to decelerate until it was going slower than the estimated centre of gravity of the cartwheeling dummy.

The vehicle had already performed a test at the same nominal offset with the child dummy and had accordingly sustained visible damage to the bumper skin, bumper trim insert, headlamp casing, bonnet behind the headlamp and over the suspension strut turret, wiper blade and bottom corner of the windscreen. A photo taken during preparation the day before also shows some marking, possibly damage to the same area of the bumper. The vehicle was also scheduled for a later high-speed lateral impact by a Honda Civic at 61 mile/h, so time did not permit a deeper inspection. Following the test with the AM50 pedestrian, it was not possible to discern much damage caused by that test over and above the child dummy impact, apart from the almost completely separate impact crater on the windscreen from the adult head.

A lack of much change in the damage caused by the child dummy test after the adult test was assumed to be because the bumper and bonnet, possibly also the headlamp, had either already bottomed out against the underlying components and therefore could not undergo further distortion, or were resilient enough to recover to the same extent from both impacts. On closer inspection of the video, it can be seen that there is a gap between the torso and the car for almost all the time after the pelvis impact, in agreement with the lack of further scuff marks from the adult impact. In fact, the simulation may show the same behavior, (see figure 8) although it is difficult to see if the humanoid is deforming the bonnet or if the visible profile of the bonnet, at the centerline, is masking the free movement of the torso and arm above the outboard area of the bonnet where it is lower.

In the high-speed car-to-car impact, the violent rotation of the Focus causes the left headlamp and bumper corner, neither of which contacted the Honda, to move noticeably relative the rest of the vehicle, indicating that the bumper had already sustained damage and that the headlamp had been pushed in as intended by one or both prior pedestrian tests.

DISCUSSION

Comparing the physical and simulated impacts, it can be seen that the overall motion is very similar, with deviations mainly in the later stages of leg motion. This is to be expected because the higher speed of the test imparts a more rapid rotation of the legs about the pelvis before the torso is fully accelerated, due to the joints' stiffness and leg segments' masses relative to torso inertia. Not only is the gross motion in broad agreement, the contact locations and modes are noticeably correlated. Where the comparison perhaps disappoints is in the quantitative aspect, not so much as disagreement but in the difficulties caused by lack of data. On the one hand, the time elapsed since the work of Howard and colleagues, and the impracticalities of storing large amounts of simulation output data, it was not possible to retrieve individual simulation results of interest to this study, such as start and end timings of contacts between the vehicle areas and the pedestrian segments for this individual case, the results for which were published in aggregate. Normal practice is to retain the models and re-run the simulations when necessary, and a certain amount of work would be necessary to modify the model to run with current versions of the FE software. That facility and the resources were unavailable at this time.

On the other hand, the purpose of the ITAI Crash Day is a blend of training and demonstration for the benefit of practicing road traffic collision investigators, together with an element of research. The information to be acquired is therefore designed to provide a known reference baseline against which post-collision investigation procedures and skill levels can be assessed. The test environment for this exercise is therefore more of a safe and secure version of a real-world crash location than like a typical crash test laboratory used primarily for product development to meet legal, corporate, consumer and insurance performance targets. Procedures have evolved to give the highest possible consistency and quality of results. Vehicles and dummies are intensively instrumented as required, and prepared for maximum contrast for high speed video analysis, the lighting is intense and the test area is optimized again for best clarity of video output. Although the child dummies were dressed in overalls having a high contrast against the dense foliage in the background, the dark blue of the adult overalls were not as helpful. The looser fit overall is more representative of the real world than the tight-fitting thin cotton garments prescribed by crash test legislation, but caused difficulty in discerning the dummy motion inside the clothing. To avoid confusing reflections, particularly of dummies on the surface they are approaching, test vehicles are often covered in contrasting matt paints, despite all of which neither manual nor automated video analysis is entirely straightforward. Finally, the data acquisition and processing pathway is planned for effectiveness and efficiency.

Beyond this, even with the original high-speed video, frame rate and frame count discrepancies currently attributed to incompatible software have made conclusions on timing of the stages of dummy motion difficult to reach with confidence: work therefore continues.

A further, unexpected, issue was that the crash test markers at intervals along the side of the car were too distorted and blurred to assist scaling the high-speed video; instead, the wheelbase was used to scale the images, the wheel centres being easier to determine. It must be remembered that accuracy can be compromised by the kinematics of the suspension during braking or steering which causes the instantaneous wheelbase to change. This was not seen as a significant effect on the Focus, and no compensation was applied.

Both the computer simulation and the dummy had been validated previously to a satisfactory level so validation was not a consideration here, and the happy coincidence of a test closely corresponding to a pre-existing simulation was seen as an opportunity to understand the relative limitations of each, particularly in regard the ongoing issue of pedestrian throw distances as an indication of vehicle velocity which has a history of many decades. There is however some evidence here of consistency of pedestrian contact locations on the vehicle despite differing speeds, confirming Howard's assertion that initial impact locations, and pitching, can have a significant effect on throw distance, also implying that vehicle shape and vehicle energy absorption are similarly influential. This merely confirms the many opinions in literature already cited that procedures and equations are reliable but only within stated, or even unstated, domains.

It was not possible to ascertain the exact reason the front wheels only locked when they did, as the dummy head impact and rebound reaction appears to have a direction that would pitch the front upwards. The suspension and damping would need to be investigated to answer that question.

During the earlier Jaguar and Ford research, field cases [Morris et al, 3] highlighted the importance of fracture of the tibia to both the injurious contacts and the trajectory. Until Yang's improvements [40] with a multi-segment lower leg, MADYMO did not represent that behaviour in a model. However, to allow a simulation to determine the point of failure in a non-arbitrary manner, Howard had used the finite element approach [1]. These two approaches have since converged to a great extent [see for example van Rooij et al, 41], though each still has its advantages and disadvantages particularly in computing resources and flexibility, so that the combination of FE for detailed interaction and MADYMO for overall responses is often employed.

CONCLUSIONS

A comparison was made between a previous computer simulation and a coincidentally similar test with an expendable low-cost dummy. The simulation represented a 50th percentile adult male humanoid pedestrian struck by a Ford Focus Mk.I at 40 km/h with an initial contact 500mm to the left of the vehicle centerline. The pedestrian faced perpendicularly away from the centerline in an upright stance with its feet in alongside each other. The test was exactly the same configuration except the speed was 55 km/h and the offset was between 600 and 680mm.

Although the motion of the dummy and the humanoid were very similar until after head impact to the windscreen, the legs of the dummy increasingly rotated further throughout and especially during free flight. This is believed to be due to the legs being accelerated faster because of the higher speed of impact, while the pelvis impact was less sensitive to the speed due to the lower front of the vehicle.

It was not possible to obtain reliable timing for the physical contact events, which will be addressed, nor was a complete trajectory available from the simulation. However, the results add to the growing and conflicting pool of evidence regarding the relationship between vehicle speed and throw distance in real world pedestrian collision cases, and many other factors of vehicle shape, stiffness, pitch due to braking, the deceleration itself, orientation and action of the pedestrian before and at impact.

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