The Relationship of AIS to Peak Virtual Power

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ABSTRACT:

It has been shown elsewhere that by using Continuum Damage Mechanics, based on the formalism of the theory of Irreversible Thermodynamics, that the concept of Peak Virtual Power (PVP) is a self-consistent indicator of damage. It is here postulated that injury severity is proportional to Peak Virtual Power, and PVP in the form of $PVP = K\Delta V^3$ is compared to AIS scores for frontal Impact with belted drivers, for all types of injuries and all body regions, from the Co-operative Crash Injury Study (CCIS) and NASS-CDC databases. The sample size in CCIS was 455 belted drivers for ΔV and 934 for ETS, whereas for NASS-CDC it was 2933. It is shown that there is very good correlation between AIS scores and PVP for all types of injuries so far investigated. Correlation's were also conducted with AIS and ETS, the trends were virtually identical. The correlations obtained show that the AIS score is linearly proportional to Peak Virtual Power, and although phenomenological, AIS measures a physical quantity. It is concluded that there appears to be a "Master Curve" of AIS versus mean DeltaV for car occupants, implying that the amount of power for a given injury level is a constant. There appear to be significant differences between the AIS scores for abdominal injuries between CCIS and NASS-CDC, and detailed case studies should be conducted in that area to resolve the differences.

Quantitative injury scaling is fundamental to safety research, and the development of safer road vehicles. The primary thrust in safety research is to map occupant injury severity onto the severity of the vehicle collision. Injury scaling, as a means of classifying the severity of impact trauma has a long history. Some of the earliest research into impact trauma was conducted at Cornell University Medical School in 1952 by De Haven and colleagues (Petrucelli 1993), and related to aircraft crashes. The sixties saw many pivotal developments when a number of first generation methodologies were also proposed by: Robertson et.al. (Robertson, McLean et al. 1966)Nahum et.al. (Nahum, Siegel et al. 1967), Mackay (Mackay 1968), Van Kirk and Lange (Van Kirk and Lange 1968), States and States (States and States 1968), Keggl (Keggl 1969), Cambell (Cambell 1969). In 1968 Ryan and Garrett (Ryan and Garrett 1968) revised De Haven's scale, and considered energy dissipation as well as threat to life as criteria. The Comprehensive Research Injury Scale (CRIS) was developed around energy dissipation and threat to life:

	Energy Dissipation	Threat to Life
Level 1	Little	None
Level 2	Minor	Minor
Level 3	Moderate	Moderate
Level 4	Major	Severe
Level 5	Maximum	Maximum

The Abbreviated Injury Scale (AIS) was first officially published in 1971 (Association 1971), revised in 1974 and 75 and published in manual format in 1976 (Scaling 1976). In between these times Baker et.al. (Baker 1974) had studied over 2000 vehicle occupants, pedestrians, and other road users and had found that the AIS score was non-linear. Further, it was found that the death-rate of person's with two or more injuries was not simply the sum of the AIS scores; this led to the introduction of the Injury Severity Score (ISS) . This is the square root of the sum of squares of the two most severe AIS scores (Baker 1974).

The AIS scale has been continuously improved and revision's were published in 1980, 85, and the current scale AIS90 in 1990. The AIS score has proven to be the "system of choice" (Petrucelli 1993), and has been documented in hundreds of articles (Medicine 1983).

Many injury criteria have been proposed, including: acceleration criteria (Eiband 1959; Stapp 1970), force criteria (Patrick, Kroell et al. 1965; Gadd and Patrick 1968), compression criteria (Neathery, Kroell et al. 1975; Kroell, Schneider et al. 1981), the viscous criterion [Lau, 1986 #29, the peak angular acceleration and the peak change in angular velocity (Margulies and Thibault 1989), and power. The suggestion of power as a correlate for Impact Trauma was apparently first formally suggested by DiLorenzo (DiLorenzo 1976), who was critical of the lack of a physical basis for HIC, and attempted to also introduce Jerk; this approach was not developed further. Waller (Waller 1985) stated: "If [the] energy reaches tissues, the rate of that energy transfer *(ideally described in units of energy per unit of body tissue per unit of time)* determines the severity of injury". Julian Waller intuitively arrived at this conclusion from experience of trauma covering a wide variety of energy sources (Waller 2001); this proposal was however not quantified. Wang (Wang 1989) showed that the "Viscous Criterion" (Lau and Viano 1986) was not a function of viscosity, but was a measure of stored energy, and proposed that the rate of viscous energy dissipated in the Thorax should be investigated as an injury criterion; however this was not followed up. Recently Newman et.al. (Newman, Beusenberg et al. 1999; Newman, Barr et al. 2000) conducted a number reconstructions of head collisions in American Football games. They conducted Logistical Regression on moderately severe injuries against a number of correlates and found the best fit was given by power, which they termed the "Head Impact Power" (HIP).

THEORY:

Biomechanical injuries result in the straining or separation (fracture, shearing, tearing or rupture) of biological tissues. The tissues themselves, as opposed to the structures (organs) in which they are arranged, generally have a high Bulk Modulus, as they are either water or Collagen based (Yamada 1970; Wainwright, Biggs et al. ; Chaffin and Andersson 1984). Soft biological tissues can be modelled as "nearly incompressible" visco-elastic-plastic materials (Chaffin and Andersson 1984; Nordin and Frankel 1989), and bone as elastic-plastic (Haut ; Yamada 1970; Wainwright, Biggs et al. ; Chaffin and Andersson 1984). In (Sturgess 2001) it is considered that injuries in Impact Trauma may be viewed as "mechanical dissipative processes" i.e. they require an expenditure of work. This theory is partly repoduced here for completeness. Modelling involves predicting the future, and all that is known of the future is that Entropy must increase, as a consequence of the Second Law of Thermodynamics. Irreversible thermodynamics features the Clausius-Duhem Inequality, which is a consequence of the Second Law (Prigogine 1961; Jou, Casa-Vazquez et al. 1993). This equation gives a formalism for deriving constitutive equations for irreversible dissipative processes, which since the 1980's has been applied to a number of flow and damage problems in continuum mechanics (Krajcinovic 1983; Krajcinovic and Lamaitre 1986; Chaboche 1988; Chaboche 1988; Lamaitre and Chaboche 1990).

The concept of virtual power has been used extensively to accurately formulate various theorems in the mechanics of materials, and has recently been applied to Impact (Sturgess 2001). If the process is chemically and electrically neutral, the Clausius-Duhem Inequality for small deformation of incompressible bodies is (Jou, Casa-Vazquez et al. 1993):

$$\sigma : \dot{\varepsilon} - \rho\left(\dot{f} + s\dot{T}\right) - \frac{1}{T} q.\nabla T \geq 0 \tag{1}$$

where: σ = Stress Tensor, $\dot{\varepsilon}$ = Total Strain Rate Tensor, ρ = Mass Density, f = Helmholtz Free Energy, s = Entropy, T = Absolute Temperature, q = Heat Flux Vector

This is a Tensor equation as it is must be invariant to transformations. Proceeding according to (Krajcinovic and Lamaitre 1986) assuming that the total strain tensor can be decomposed into the elastic and plastic (reversible and irreversible) strain tensors as:

$$\varepsilon = \varepsilon^{e} + \varepsilon^{p} \tag{2}$$

This decomposition applies to both elastic-plastic and visco-plastic materials (Lamaitre and Chaboche 1990). The appropriate form of the Helmholtz Free Energy (the constitutive relationships) (Jou, Casa-Vazquez et al. 1993) may be described as a function of the following variables:

$$f = f\left(\varepsilon^{e}, D_{ij}, T\right) \tag{3}$$

where ε^{e} = the elastic strain tensor
D_{ij} = the "Damage Tensor"

Now differentiating (3) and substituting in (1) gives the specific rate of entropy production ($\dot{\Phi}$) as:

$$\rho\dot{\Phi} = \sigma : \dot{\varepsilon}^{p} - \rho\left(\frac{\partial f}{\partial D_{ij}}\right)\dot{D}_{ij} - \frac{1}{T} q.\nabla T \geq 0 \tag{4}$$

This equation can be developed to derive the Maxwell, Huber, von-Mises, Hencky yield criterion, and the fundamental equations of Fracture Mechanics (Murakami 1988; Murakami and Kamiya 1997; Li 1999)

For a mechanical system, assuming the contribution of heat flux can be decoupled (Lamaitre and Chaboche 1990),

$$\sigma : \dot{\varepsilon}^{p} \geq \rho\left(\frac{\partial f}{\partial D_{ij}}\right)\dot{D}_{ij} \quad \text{or} \quad \sigma : \dot{\varepsilon}^{p} \propto \dot{D}_{ij} \qquad (5)$$

If sufficient data is available the form of the self-consistent constitutive equations and the damage evolution function can be determined, see (Krajcinovic 1983; Krajcinovic and Lamaitre 1986; Chaboche 1988; Chaboche 1988; Murakami 1988; Lamaitre and Chaboche 1990) equation (5) could be integrated. However, for biological systems these functions are not yet known.

Equation (5) shows that the Virtual Power, i.e. product of stress and strain-rate, is proportional to the rate of damage production and should be a predictor of the rate of injuries in Impact Trauma, provided these are dominated by mechanical dissipation. It may also be defined as:

$$\frac{1}{m}\left(\frac{\partial U}{\partial t}\right) \propto \frac{1}{\rho}\left[\frac{\partial\left(U/V\right)}{\partial t}\right] \propto \frac{\partial}{\partial t}\left[\sigma_{e}\varepsilon_{e}^{p}\right] \propto \sigma_{e}\left(\frac{\partial \varepsilon_{e}^{p}}{\partial t}\right) \propto \sigma_{e}\dot{\varepsilon}_{e}^{p} \qquad (6)$$

where $\frac{\partial\left(U/V\right)}{\partial t}$ = power per unit volume

σ_e = Equivalent Stress and

$\dot{\varepsilon}_e^p$ = Equivalent Plastic Strain Rate

Equivalent stress and strain must be used as they are Invariant.

From which if equations (5) and (6) are compared, it can be that virtual power is proportional to the rate of damage production which is also proportional to the rate of specific entropy production; this was also identified by Martin (Martin 1975). However, power is not necessarily unique, but “Peak Virtual Power” (PVP) is unique and will be defined as:

$$PVP = \frac{1}{\rho}^{\Uparrow}\left[\frac{\partial\left(U/V\right)}{\partial t}\right] = {}^{\Uparrow}\left|\sigma_{ij}\dot{\varepsilon}_{ij}^{p}\right| \qquad (7)$$

This is a damage model, and it is necessary to map injuries on to damage. Here it is postulated that the severity of injuries in Impact Trauma are proportional to the energy input to the system. For a given impact, over a given time interval, the amount of damage (severity) will be proportional to the rate of damage production times the time interval, a “rate”, “dosage”, or “exposure” criterion then becomes:

$$\text{Severity of } Injury \propto D \propto \left(\dot{D}_{ij}\right)\Delta t \propto \left(\sigma_{ij}\dot{\varepsilon}_{ij}{}^{p}\right)\Delta t \propto PVP \qquad (8)$$

RESULTS AND DISCUSSION

It has been shown (Sturgess, Hassan et al. 2001) that Peak Virtual Power can model the severity of injury at the micro, meso and macro scales, and can model head impact injuries as well, if not better than, HIC. Alternative forms of Virtual Power $\left(\sigma : \dot{\varepsilon}^p\right)$ are:

1. As $\sigma \propto \varepsilon \propto \Delta \propto \hat{\Delta}$ then $\sigma : \dot{\varepsilon}^p \propto \hat{\Delta}\hat{V}$, which is the "Viscous Criterion" (Lau and Viano 1986).
2. $\sigma \propto F \propto a \propto \hat{a}$ and $\dot{\varepsilon}^p \propto V \propto \hat{V}$, therefore $\sigma : \dot{\varepsilon}^p \propto \hat{a}\hat{V}$ which is the "Margulies and Thibault" criterion (Margulies and Thibault 1989), with 'a' as a generalised acceleration.

therefore, existing correlations with the above criteria are here taken as confirmation of the concept of Peak Virtual Power. The concept of PVP also applies to "Blast Injuries" (Clemedson 1956; Smith, L'Abbe et al. 1990; Stuhmiller 1997), and certain phases of air bag deployment (Horsch, Lau et al. 90), which is not surprising when it is remembered that the genesis of the Viscous Criterion is blast loading (Stuhmiller 1997). This will be the subject of a future publication (Sturgess 2001)

Restrained Occupants: Of particular interest here is the ability of Peak Virtual Power to model meso and macro scale injuries in the Real-World. These concepts can be applied to the impact of a rigid body travelling at velocity V, impacting a deformable structure with a ride-down of S over a time Δt, at a constant deceleration, Fig.1. This crash pulse is ideally applicable to a fully restrained occupant, as the crash pulse experienced by both car and occupants are the, and is therefore a "fully coupled" problem:

Subscript 'c' relates to the vehicle, subscript 'o' relates to the occupant.

Then peak power per unit mass is

$$\frac{1}{m}\left(\frac{\partial \hat{U}}{\partial t}\right) = a.V \qquad (9)$$

There will be a unique value of Peak Virtual Power for each crash pulse, the challenge is to relate the severity of injury (PVP) of the occupants to the crash severity for the vehicle, categorised by ΔV or ETS as computed from CRASH3 (Smith and Noga 1982).

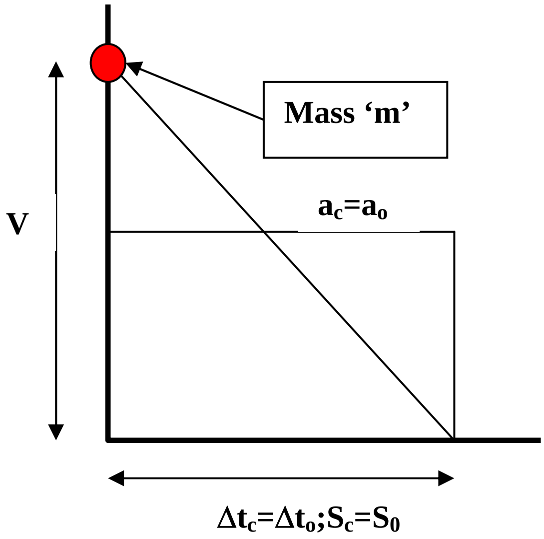

Fig.1. Impact for Restrained Occupants

Therefore what is required is to express PVP for occupant as a function of the ΔV of the vehicle. Returning to Fig.1, the simplified fully coupled impact for restrained occupants:

from equation 11, as $a = \frac{V}{\Delta t}$ therefore $\frac{1}{m}\left(\frac{\partial \hat{U}}{\partial t}\right) = \frac{V^2}{\Delta t}$ (10)

To render this measure specific to the vehicle it is necessary to normalise on the vehicle ride-down. This expresses the power per unit mass for the occupant as a function of the severity of collision of the vehicle. Normalising on the vehicle ride-down for this pulse, $S_c = \frac{V}{2}\Delta t$ then:

$$PVP = \frac{S_c}{m}\left(\frac{\partial \hat{U}}{\partial t}\right) \propto V^3 \overset{\sim}{\propto} \Delta V^3 \propto (ETS)^3 \qquad (11)$$

The severity of injury in real-world crash investigations is mostly measured using the "Abbreviated Injury Scale" (AIS) (Association 1971) , which is an "ordinal" or integer non-linear increasing scale, derived from empirical data, and expresses the probability of death from each injury sustained. Therefore, if Peak Virtual Power is a valid measure of injury severity, then it should be proportional to the maximum AIS score for the body regions. erefore for this crash pulse it is assumed that:

$$\text{Severity of Injury} \propto AIS \propto \text{PVP} \propto V^3 \overset{\sim}{\propto} \Delta V^3 \overset{\sim}{\propto} (ETS)^3 \qquad (12)$$

which should apply for restrained occupants. Over 70 correlations have so far been conducted and all show excellent agreement. What are shown below are a selection from these results to illustrate the scope and nature of the correlations.

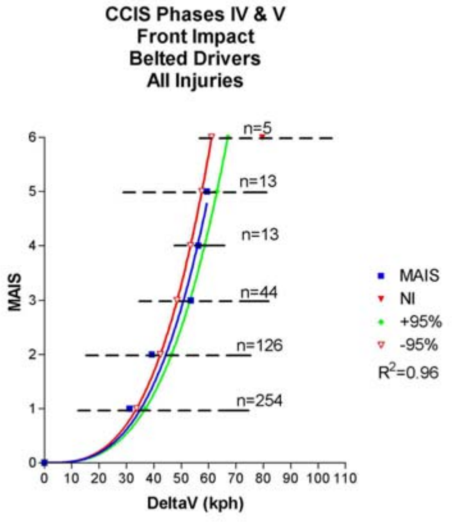

Fig.2.

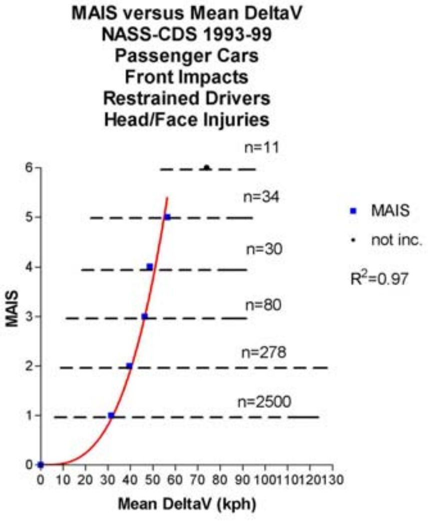

Fig.3.

Figs.2.and 3. above show typical correlations between AIS and Mean ΔV from both the CCIS and NASS-CDC databases. It can be seen that at any one level of AIS occurs over a wide range of ΔV, and the range of ΔV often diminishes the higher the level of AIS. Also at the higher levels of AIS there is often a shift of data to higher DeltaV. This maybe due to the difficulties of coding fatal injuries, and/or the inaccuracies of estimating DeltaV for very high impact velocities (Smith and Noga 1982).However, there is a clear relationship between the Mean AIS and ΔV. This means that there is a linear relationship between AIS and Peak

Virtual Power. In Fig.4. is shown one of the correlations obtained from data from the Co-operative Crash Injury Study (CCIS) (Mackay, Galer et al. 1985). This is shown for two reasons, one it is the poorest correlation so far obtained for individual body regions, with a Correlation Coefficient of 0.81/0.82, and also shows the similarities obtained for correlations with ΔV and ETS. The data sets in CCIS with a valid ΔV are far smaller than with a value for ETS, and as the correlations are always better for larger data sets, then ETS is often used in place of ΔV.

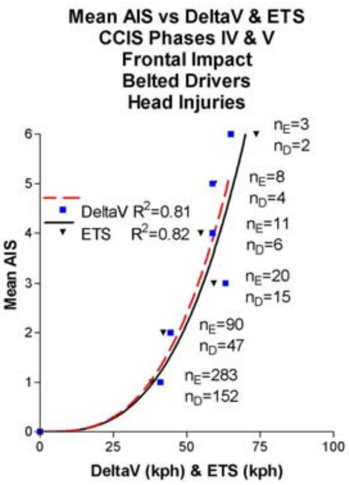

Fig.4.

Having a deterministic model permits the first non-statistical comparison between different databases, here it is chosen to compare CCIS and NASS-CDC. In Figs. 5 & 6 below are shown comparisons of CCIS and NASS-CDC for AIS levels and mean DeltaV for head and thorax; similar comparisons are available for all other body regions. It can be seen from Figs. 5 & 6 that there are small, and apparently systematic differences between CCIS and NASS-CDC. The DeltaV levels for NASS-CDC are always slightly lower than those for CCIS, except for abdominal injuries, which will be returned to later. The general effects may be due to differences in coding, differences in calculating DeltaV, or other effects. However, the differences are not significant at the 99% level, i.e. the 99% confidence limits overlap.

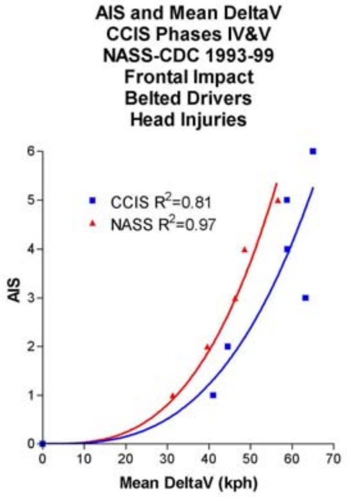

Fig.5.

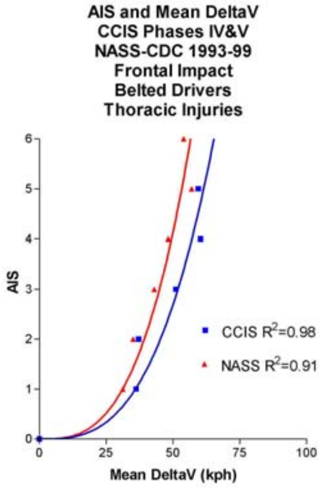

Fig.6.

In Figs. 7 and 8 are shown the collected results for all body regions from CCIS and NASS-CDC. From Fig.7, (CCIS) it can be seen that the results fall into a narrow band except for those for the abdominal injuries. In Fig.8. (NASS) all the data for all body regions fall in a narrow band. Detailed comparisons show that there are no statistically significant differences between the data for any body region between CCIS and NASS, except for abdominal injuries. Abdominal injuries are difficult to code and it is possible that, as scanning is common in the US and infrequent in the UK, then the severity of abdominal injuries in the UK could be underestimated; detailed case studies are necessary to resolve the differences in this area.

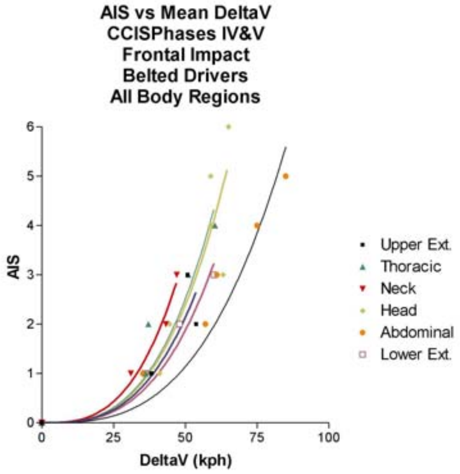

Fig.7.

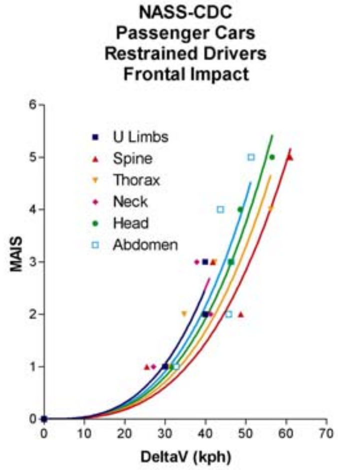

Fig.8.

In Fig.9. is shown the collected data for all body regions for both CCIS and NASS, excluding the abdominal data from CCIS, together with the 99% confidence limits for the curve through all the data. It can be clearly seen that all the data fall in a narrow corridor, and to a first degree of approximation there can be considered a “Master Curve” of AIS versus mean DeltaV. This implies that for any body region the amount of power for a given level of injury (AIS) is the same.

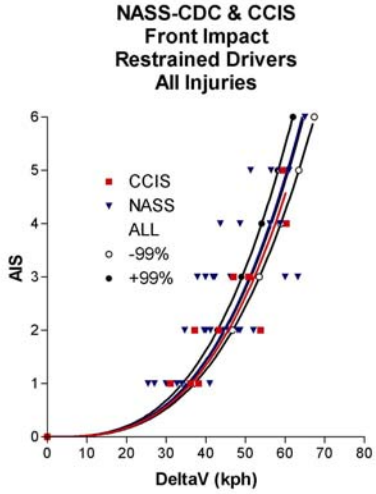

Fig.9.

Unrestrained occupants have an entirely different crash pulse, being approximately as shown in Fig.10. below, where the force/time and velocity/time profiles of the occupant are no longer the same as those of the vehicle; this is therefore a de-coupled problem. From Fig.8. it can be seen that, for the acceleration pulse shown, Peak Virtual Power occurs at $t = \Delta t/2$, and is:

$$\frac{1}{m}\left(\frac{\partial \hat{U}}{\partial t}\right) \propto \hat{a}\frac{V}{2} \propto \bar{a}^{2}\Delta t_{o} \propto \frac{V^{2}}{\Delta t_{o}} \qquad (13)$$

but in this case the relationship between the exposure time for the occupant and the vehicle ride-down is $S_c = C\Delta t_o$, where ‘C’ is a constant.

Therefore Peak Virtual Power for the unrestrained occupant, normalised on the vehicle ride-down is:

$$PVP = \frac{S_C}{m}\left(\frac{\partial \hat{U}}{\partial t}\right) \propto \hat{a}V \propto V^{2} \qquad (19)$$

and so for unrestrained occupants:

$$\text{Severity of Injury} \propto \propto AIS \propto \text{PI(\%)} \propto \text{PVP} \propto V^2 \overset{\sim}{\propto} \Delta V^2 \qquad (14)$$

Correlations for unrestrained occupants are shown in Figs. 11. and 12. below. For these correlations NASS-CDC data was chosen (Roberts and Compton 1993), as the sample size for unrestrained drivers in the CCIS Database is very small. Again the general points are very similar, the tail-off in the distribution is very evident for low AIS, and the agreement is better for higher AIS levels, and the correlations hold for 85-90% of the data .

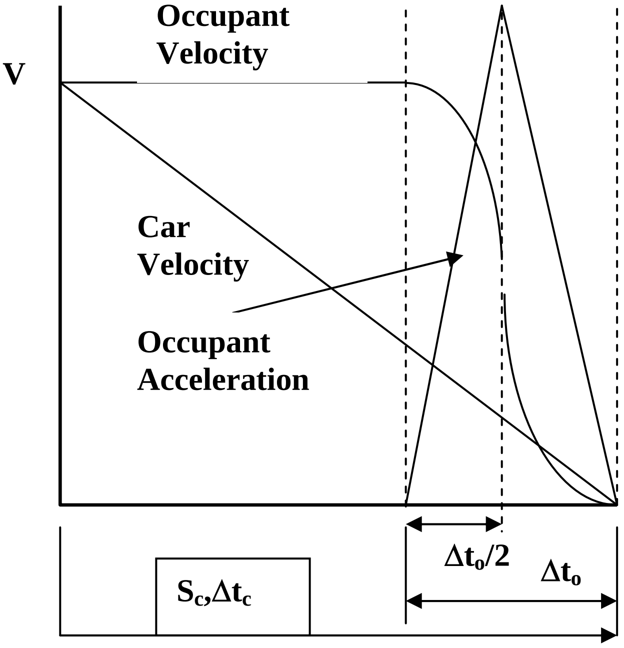

Fig.10

These correlations are for ΔV^2, whereas for the restrained occupants the relationship was ΔV^3, the main difference between the square and cubic relationships is that for the square the AIS values at lower ΔV are much higher than for the cube. This simply quantifies what is generally observable that unrestrained occupants suffer higher injury levels at lower ΔV than do restrained occupants.

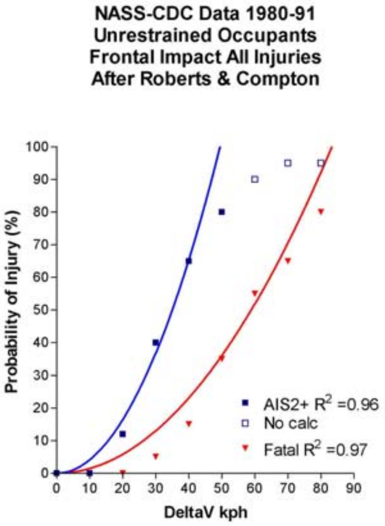

Fig.11

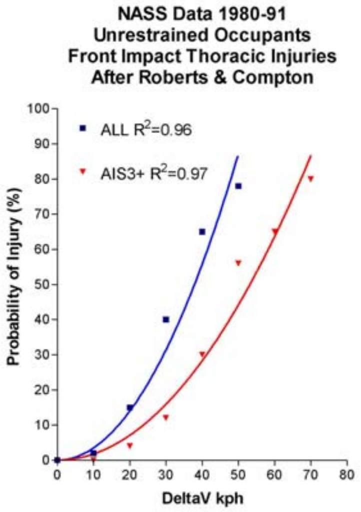

Fig.12

CONCLUSIONS

It is concluded from the work conducted to date, that Peak Virtual Power:

- is an objective, invariant, dimensionally correct, unique, injury criterion which satisfies the Second Law of Thermodynamics.
- is linearly proportional to AIS
- applies to all body regions and severities of injury
- applies to around 85% to 90% of injury data

- shows no statistically significant differences between the AIS values at a given DeltaV between the CCIS and NASS-CDC databases, except for abdominal injuries; detailed case studies should be conducted in this area
- shows what appears to be a "Master Curve" of AIS versus mean DeltaV for car occupants implying that the amount of power for a given injury level is a constant.

Acknowledgement: This paper uses accident data from the United Kingdom Co-operative Crash Injury Study (CCIS).CCIS is managed by TRL Limited, on behalf of the Department of the Environment, Transport and the Regions (Vehicle Standards and Engineering Division) who fund the project with Autoliv, Ford Motor Company, Honda R&D Europe, LAB, Toyota Motor Europe, and Volvo Car Corporation. The data were collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham; the Vehicle Safety Research Centre of the University of Loughborough; and the Vehicle Inspectorate Executive Agency of the DETR.
Further information on CCIS can be found at http://www.ukccis.com/

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