MOMENTUM AND EVENT DATA RECORDERS

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Abstract

The principle of conservation of linear momentum has long been used by collision reconstructionists to obtain estimates of initial vehicle speeds in vehicle-to-vehicle crashes. Because, in general, both vehicle speeds are unknown, the method requires extensive scene evidence to provide measures of the vehicle run-out speeds, and the approach and departure angles of the vehicles with respect to the collision. Many late-model vehicles, notably those manufactured by General Motors and Ford, are now equipped with event data recorders (EDR's) that record certain vehicle parameters when a collision occurs. Nominally, the data parameters of interest that might be available for a vehicle equipped with an EDR are the vehicle's impact speed, the change in vehicle velocity (ΔV) occurring in the collision, and the principal direction of force (PDOF) experienced by the vehicle. Effectively, EDR's provide collision investigators with one or more instrumented vehicles in the crash, and give a source of new data that can be integrated into the reconstruction process. The present work demonstrates how the recorded parameters can be utilized in momentum-based calculations, and notes the limitations that may apply to such use. It is also noted that collision situations where both EDR's and adequate scene evidence are available provide real-world "experiments" whereby the conservation of momentum methodology may be readily verified.

Résumé

Le principe de la conservation du mouvement linéaire est utilisé depuis longtemps par les spécialistes de reconstitution des collisions pour estimer la vitesse initiale des véhicules lors d'accidents entre véhicules. Étant donné que la vitesse des deux véhicules est généralement inconnue, la méthode exige la collecte de nombreux renseignements sur les lieux de l'accident afin d'établir la vitesse maximale des véhicules, ainsi que l'angle d'approche et d'éloignement avant et après la collision. De nombreux véhicules récents, notamment ceux construits par General Motors et Ford, sont munis d'un enregistreur de données de conduite (EDR), dispositif qui recueille automatiquement certains paramètres d'un véhicule lors d'une collision. En principe, les paramètres de données d'intérêt pouvant être disponibles sur des véhicules munis d'un EDR sont la vitesse à laquelle roulait le véhicule, la variation de vélocité du véhicule lors d'une collision et la direction principale de la force du véhicule. En réalité, les EDR permettent aux enquêteurs d'obtenir des enseignements sur un ou plusieurs véhicules impliqués dans une collision et fournissent de nouvelles données qui peuvent être intégrées au processus de reconstitution. Le présent document illustre la façon dont les paramètres recueillis peuvent être utilisés pour mesurer le mouvement et indique les restrictions possibles à leur utilisation. Également, il décrit des situations où des EDR et des éléments de preuve sur les lieux d'une

collision ont servi « d'expérimentation » en temps réel, permettant ainsi de vérifier facilement la méthodologie de calcul de la conservation du mouvement.

INTRODUCTION

The principle of conservation of linear momentum is based on Newton's laws of motion [1]. In particular, for a two-vehicle collision, Newton's third law indicates that the forces acting on the two vehicles must be equal and opposite. The second law specifies that the force acting on a vehicle is the product of its mass and its acceleration. Consequently, we may write:

$$F_1 = -F_2$$

$$m_1 a_1 = -m_2 a_2 \tag{1}$$

where F_1 = force acting on Vehicle 1
F_2 = force acting on Vehicle 2
m_1 = mass of Vehicle 1
a_1 = acceleration of Vehicle 1
m_2 = mass of Vehicle 2
a_2 = acceleration of Vehicle 2

Recognizing that acceleration is the rate of change of velocity (ΔV) with time (t), we may write Equation 1 as:

$$m_1 \Delta V_1 / t = -m_2 \Delta V_2 / t$$

$$m_1 \Delta V_1 = -m_2 \Delta V_2 \tag{2}$$

Writing the ΔV's in terms of the final and initial vehicle velocities gives:

$$m_1 (V_1' - V_1) = -m_2 (V_2' - V_2) \tag{3}$$

where V_1' = final velocity of Vehicle 1
V_1 = initial velocity of Vehicle 1
V_2' = final velocity of Vehicle 2
V_2 = initial velocity of Vehicle 2

Expanding Equation 3 gives the familiar linear momentum equation:

$$m_1 V_1 + m_2 V_2 = m_1 V_1' + m_2 V_2' \tag{4}$$

Since velocity, acceleration and momentum are vector quantities, Equation 4 must be solved using vector analysis, either through a graphical [2] or an algebraic solution [3]. Normally, the method is applied to vehicle-to-vehicle angled collisions where both initial speeds are unknown and two-dimensional vector analysis can provide a solution. The method can also be used for in-line crashes where the initial speed of one vehicle is available.

Historically, the application of the conservation of linear momentum to real-world motor vehicle crashes has been limited to situations where physical evidence at the crash site has provided the necessary inputs for the determination of vehicle run-out speeds plus the associated approach and departure angles and/or where reliable witness testimony has indicated the initial impact speed of one of the involved vehicles. With the advent of event data recorders, and the availability of pre-crash and crash pulse data, particularly initial speed and ΔV [4], a new source of objective data is available to the collision reconstructionist as either inputs into the momentum solution, or to provide a check on the results obtained from a conventional approach. The present work explores both of these aspects of the application of EDR's to computations based on momentum.

EVENT DATA RECORDERS AND MOMENTUM

For the purposes of this paper we will consider only EDR systems that are available in General Motors' vehicles. The parameters captured by such EDR's are dependent on the vehicle's year, make and model, and more specifically on the type of sensing and diagnostic module (SDM) with which the vehicle is equipped. Where pre-crash data are available, the EDR may yield a useful estimate of the vehicle's initial speed. If information on the crash pulse is captured, the vehicle's change in velocity in the collision may be stored as a cumulative ΔV over the time of the collision and/or as the maximum ΔV for the crash. Some EDR's have a uniaxial accelerometer and record only the longitudinal component of ΔV, while more modern units have biaxial accelerometers and provide both the longitudinal and lateral components of ΔV. The latter systems will also usually provide a measure of the principal direction of force (PDOF) acting on the vehicle during the crash.

We can see how these data can be incorporated into a solution of the equation for the conservation of linear momentum for a two-vehicle collision by considering the associated vector diagram (Figure 1). For convenience, angles are measured using the initial direction of travel of Vehicle 1 as the reference datum of zero degrees. The departure angle of Vehicle 1 is θ_1', while the approach and departure angles of Vehicle 2 are θ_2 and θ_2' respectively.

In the triangle ABE, note the addition of vectors EA (which acts in the opposite direction to AE) and AB:

$$EA + AB = EB = -m_1V_1 + m_1V_1' = m_1V_1' - m_1V_1 = m_1(V_1' - V_1) = m_1\Delta V_1$$

Thus the vector EB represents the change in momentum of Vehicle 1 ($m_1\Delta V_1$) that resulted from the collision.

Similarly, in the triangle BEC:

$$BC + CE = BE = m_2V_2' + (-m_2V_2) = m_2V_2' - m_2V_2 = m_2(V_2' - V_2) = m_2\Delta V_2$$

so that the vector BE represents the change in momentum of Vehicle 2 ($m_2\Delta V_2$) that resulted from the collision.

Note that vector EB has the same magnitude as, but acts in the opposite direction to, vector BE. Thus, it can be seen that these two vectors are a graphical representation of Equation 2, based on the magnitudes of the vectors being the product of the mass (m) and change in velocity (ΔV) of each vehicle.

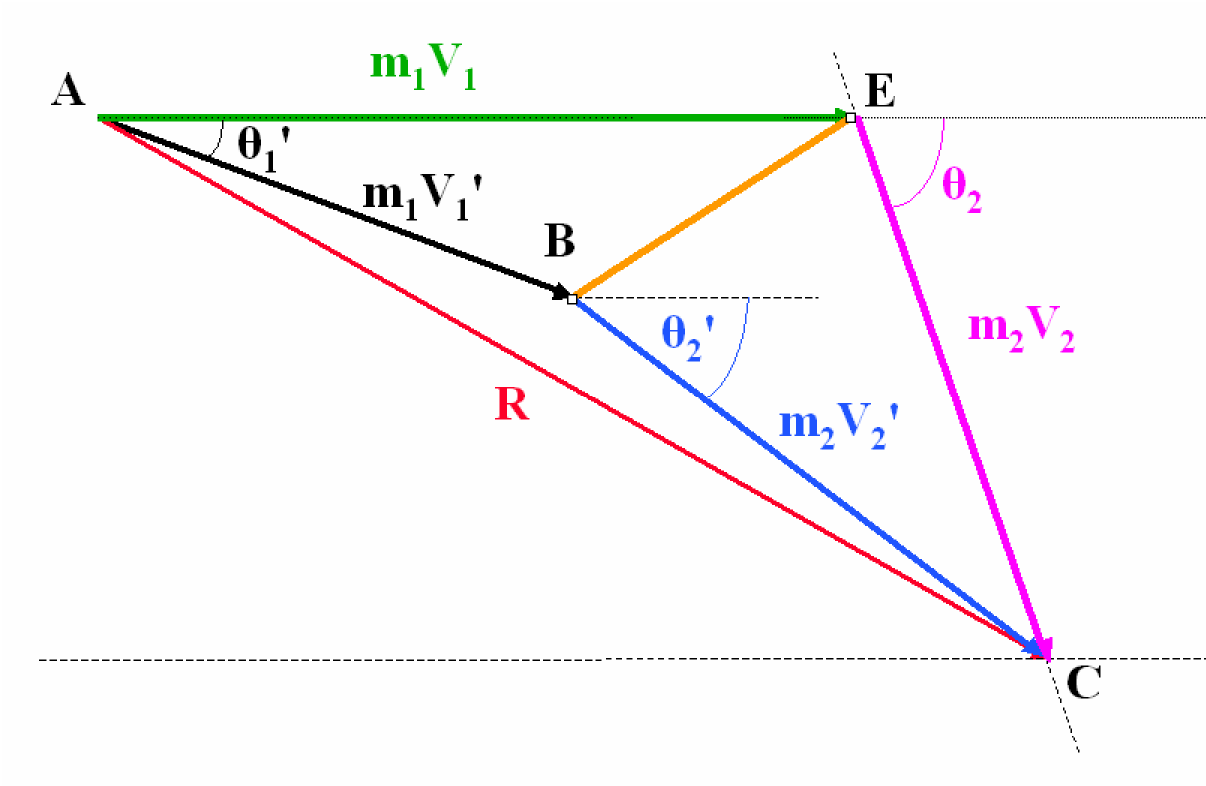

Figure 1 Pre- and post-impact momentum vectors for a vehicle-to-vehicle collision

Note that the line of action of the vectors EB and BE also defines the principal directions of force for the two vehicles since the forces, the vehicle accelerations and their changes in velocity must all act along the same line (Figure 2).

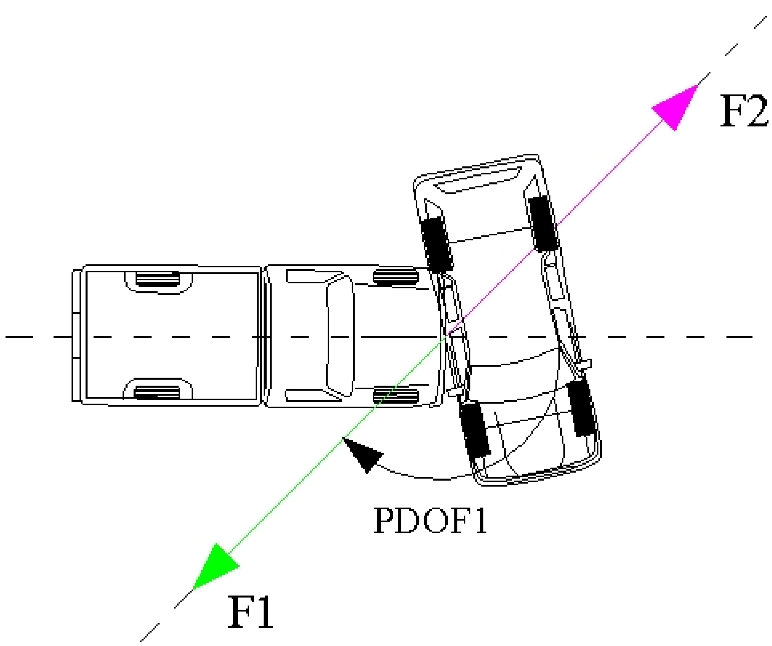

Figure 2 Principal Direction of Force (PDOF)

Depending on the end use of the data, a mathematical reconstruction of a collision may be undertaken to provide estimates of the initial speed of each vehicle and/or their changes in speed. As noted earlier, using momentum, this is normally achieved using data collected from the collision scene to identify the approach and departure angles of the involved vehicles, and computing their run-out speeds based on their post-impact trajectories. With these data elements, the vector diagram for the vehicle momenta can be drawn and the desired parameters determined.

However, as noted above, EDR's can provide estimates of some of the required input parameters and these may be readily incorporated into the momentum solution.

EDR provides longitudinal delta-V (ΔV_{1X})

If the EDR provides a valid estimate of the longitudinal component of the vehicle's change in velocity (ΔV_{1X}) resulting from the crash, and we can estimate the principal direction of force acting on the vehicle ($PDOF_1$), then we can compute the vehicle's total change in momentum ($m_1\Delta V_1$).

Knowing the mass of Vehicle 1 and the longitudinal component of its ΔV we can compute the magnitude of the change in momentum along the longitudinal axis of Vehicle 1 as $m_1\Delta V_{1X}$. In general, this vector will act in the opposite direction to the initial velocity (V_1) of Vehicle 1 and thus can be represented on a vector diagram as shown in Figure 3.

The vehicle's PDOF can usually be estimated from an evaluation of the crush damage profile, the orientation and run-out trajectory of the vehicle at the collision scene, and the location of any occupant contacts with the vehicle interior. We know that the total ΔV for Vehicle 1 must act along its PDOF and thus we can construct the vector triangle shown in Figure 3, since the lateral and longitudinal components of the vehicle's ΔV must be perpendicular. From this vector triangle we can obtain the vector representing the total change in momentum of Vehicle 1 in the collision ($m_1\Delta V_1$).

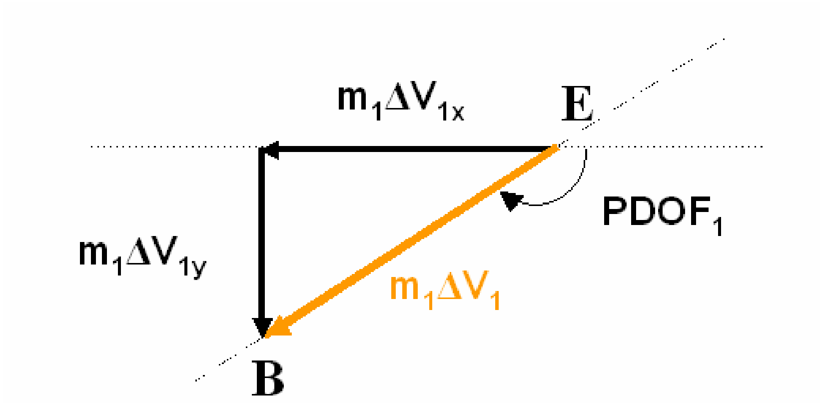

Figure 3 Components of the total change in momentum

If we wish to obtain the initial speeds of the two vehicles (V_1 and V_2), then, in addition to the vector representing the total change in momentum of Vehicle 1 derived above, we will need to know the departure angle of Vehicle 1 (θ_1'), and the approach and departure angles of Vehicle 2 (θ_2 and θ_2'), in order to construct the complete vector diagram shown in Figure 1 and perform a conventional momentum analysis from this point.

EDR provides initial speed (V_1) and longitudinal delta-V (ΔV_{1X})

If the EDR provides a reasonable estimate of the vehicle's speed at impact, and a measure of the longitudinal component of its change in velocity, we could proceed as noted above. However, the vehicle's PDOF, being estimated from a variety of key indicators, is normally subject to greater uncertainty than the vehicle's departure angle since the latter is based on specific physical evidence identified at the collision scene (e.g. tire marks, gouges, fluid spills, etc.) Consequently, it is preferable in this case, to determine the vector representing the initial momentum of Vehicle 1 (m_1V_1), the longitudinal component of its change in momentum ($m_1\Delta V_{1X}$) and hence the line of action of the normal component, and integrate these with the vehicle's departure angle (θ_1') to develop the vector diagram shown in Figure 4. The vector diagram may then be completed and the reconstruction accomplished as indicated previously.

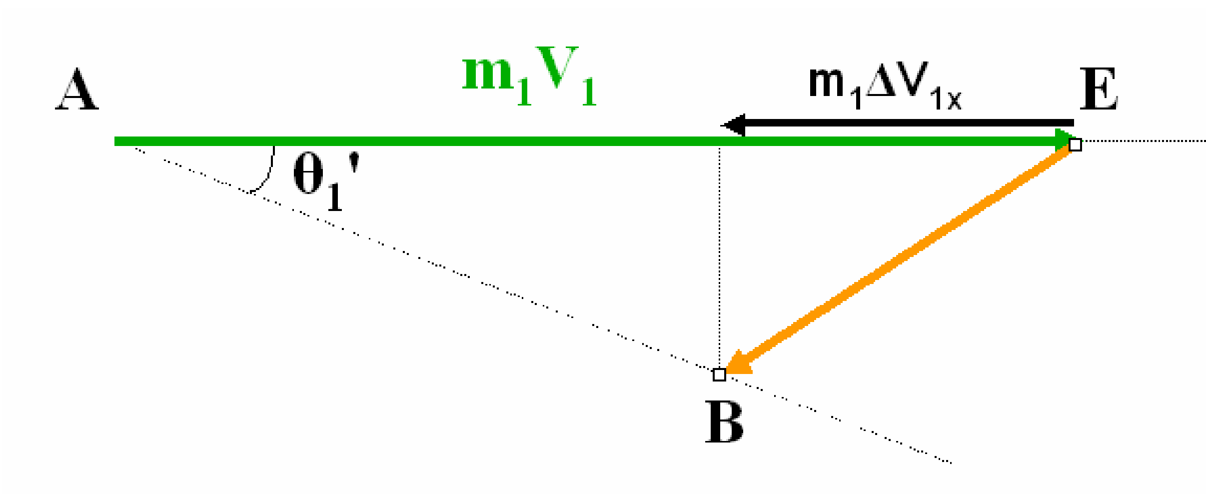

Figure 4 Derivation of the total change in momentum using Vehicle 1's departure angle

EDR provides initial speed (V_1), longitudinal delta-V (ΔV_{1X}), lateral delta-V (ΔV_{1Y}), and PDOF

The most recent generation of General Motors' SDM's provide measures of both the longitudinal and lateral components of the vehicle's ΔV. Clearly, these can be combined (Figure 3) to determine the total ΔV as:

$$\Delta V_1 = \sqrt{(\Delta V_{1X}^2 + \Delta V_{1Y}^2)} \quad (5)$$

Thus, the EDR allows us to compute the vehicle's initial momentum (m_1V_1), its change in momentum ($m_1\Delta V_1$), and gives the principal direction of force acting on the vehicle ($PDOF_1$), so that we may construct the vector diagram shown in Figure 5.

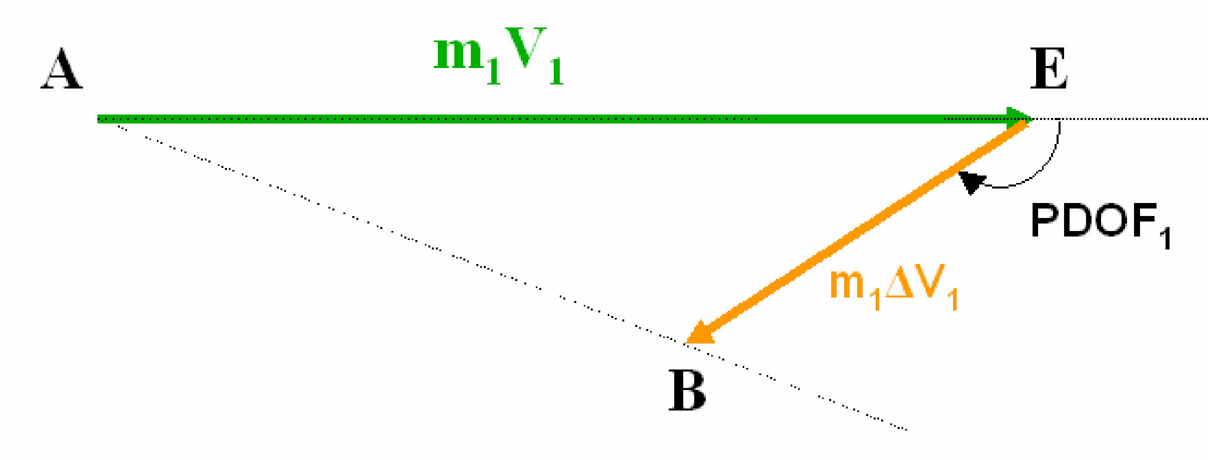

Figure 5 Vector diagram using V_1, ΔV_1, and PDOF

Note that the information provided by the EDR in this case effectively eliminates the need to know Vehicle 1's departure angle so that this measure, developed from evidence collected at the collision scene, provides a redundant check on the accuracy of the vector diagram.

The approach and departure angles of Vehicle 2 may now be incorporated into the vector diagram in order to complete the solution of the conservation of momentum equation as noted previously.

CASE STUDIES

The following examples of the use of the methods described above are taken from in-depth investigations of real-world crashes conducted by the authors and by some of Transport Canada's university-based research teams:

2001 Buick Century/1997 Buick LeSabre/Side Impact

The case collision occurred during daylight hours on a two-lane, undivided, urban freeway. The asphalt-paved roadway was dry with a posted speed limit of 80 km/h. A 1997 Buick LeSabre was merging into the southbound lane when it was struck in the left-rear corner by the right-front end of a 2002 Oldsmobile Intrigue that was occupying the lane. The impact re-directed the LeSabre across the roadway centreline and into the path of a northbound 2001 Buick Century. The front end of the Century struck the rear-right side of the LeSabre. Both vehicles rotated out of the collision, the Century coming to rest just north of the point of impact, and the LeSabre coming to rest in the ditch on the east side of the road.

For the purposes of a momentum analysis, collision investigators determined the following parameters:

2001 Buick Century	1997 Buick LeSabre
$m_1 = 1528$ kg	$m_2 = 1555$ kg
$\theta_1 = 0°$	$\theta_2 = 154°$
$\theta_1' = 7.6°$	$\theta_2' = 103.7°$
$V_1' = 18.8$ km/h	$V_2' = 25.4$ km/h

The magnitudes of the final momentum vectors are thus:

$$m_1V_1' = 1528 \times 18.8 = 28726 \text{ kg km/h}$$
$$m_2V_2' = 1555 \times 25.4 = 39497 \text{ kg km/h}$$

and the momentum vector diagram may be drawn as shown in Figure 6:

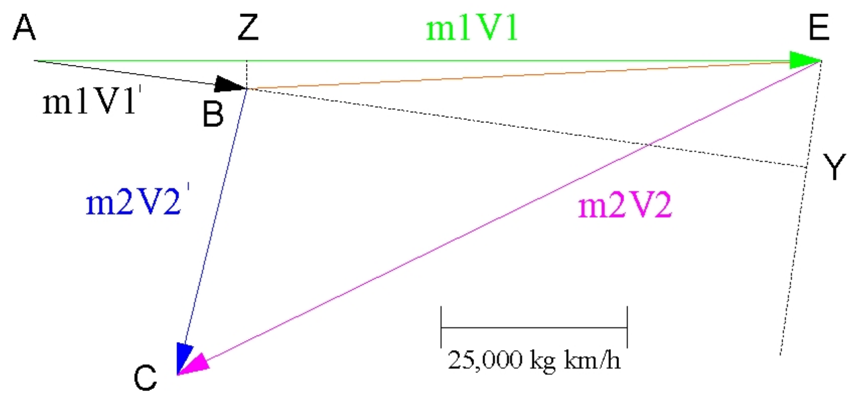

Figure 6 Momentum vectors - 2001 Buick Century (Vehicle 1)/1997 Buick LeSabre (Vehicle 2)

From the scale diagram, the vector AE, the initial momentum of Vehicle 1 (m_1V_1), is found to have a magnitude of 105,586 kg km/h, and EC, the initial momentum of Vehicle 2 (m_2V_2), has a magnitude of 96,203 kg km/h. Thus:

$$V_1 = 105{,}586 / 1528 = 69 \text{ km/h}$$
$$V_2 = 96{,}203 / 1555 = 62 \text{ km/h}$$

The vector EB is the total change in momentum of Vehicle 1 ($m_1\Delta V_1$) and has a magnitude of 77,206 kg km/h. Thus:

$$\Delta V_1 = 77{,}206/1528 = 50 \text{ km/h}$$

Similarly, vector EZ is the longitudinal change in momentum for Vehicle 1 ($m_1\Delta V_{1X}$), with a magnitude of 77,112 kg km/h, so that:

$$\Delta V_{1X} = 77{,}112/1528 = 50 \text{ km/h}$$

The Buick Century was equipped with an EDR which gave both pre-crash and crash pulse data. The maximum longitudinal ΔV recorded by the EDR was 48 km/h (29.63 mph) which compares favourably to the value determined from the momentum analysis. The Century's speed was reported as 77-79 km/h (48-49 mph) for the first four seconds of the five-second interval prior to algorithm enable (AE), with 5% throttle engagement, and the brake switch circuit being off. In the final second, the throttle readout went to zero, the brake switch circuit status changed to on, and the vehicle's speed was recorded as 76 km/h (47 mph). The driver of the Buick Century indicated that he was initially travelling at the posted speed limit of 80 km/h using the vehicle's cruise control and that just prior to the crash he braked hard. The momentum analysis supports this scenario since full braking (0.7g) for approximately 0.25 s would account for the reduction in the vehicle's speed from the 76 km/h reported by the EDR to the value of 69 km/h determined by momentum.

At the point of impact, although the centre of gravity of the Buick LeSabre had an approach angle of 154°, the vehicle actually had a heading angle of 98° and was slipping sideways with a slip angle of 56°. This vehicle was also equipped with an EDR that reported its longitudinal ΔV in the crash as 11 km/h (6.8 mph). On the momentum diagram, vector YE is oriented along the vehicle's heading angle so that this vector represents the longitudinal change in the vehicle's momentum. From the scale diagram, we can obtain the magnitude of this vector ($m_2 \Delta V_{2X}$) as 14,494 kg km/h. Thus, our momentum analysis gives:

$$\Delta V_{2X} = 14{,}494 / 1555 = 9.3 \text{ km/h}$$

showing reasonable agreement with the value reported by the EDR.

2002 GMC Sierra/1999 GMC Jimmy/Side Impact

A 1999 GMC Jimmy utility vehicle was westbound on a two-lane, undivided, secondary road and approaching an intersection with a north-south highway. The driver of the Jimmy failed to bring the vehicle to a halt at a stop sign and entered the intersection. A 2002 GMC Sierra pickup truck was travelling southbound in the curb lane of the major road. The front of the Sierra struck the right side of the Jimmy and both vehicles ran off the road into the ditch on the south-western corner of the intersection. The collision occurred in daylight hours, and with clear visibility. Both roadways were asphalt-paved and dry. The posted speed limits were 100 km/h for the highway and 90 km/h for the secondary road.

The original collision investigators identified the approach and departure angles for the two vehicles, but did not compute their run-out speeds. The following parameters were determined for the two involved vehicles:

2002 GMC Sierra	1999 GMC Jimmy
$m_1 = 2731$ kg	$m_2 = 2096$ kg
$\theta_1 = 0°$	$\theta_2 = 90°$
$\theta_1' = 10°$	$\theta_2' = 33°$

The 2002 GMC Sierra was equipped with an event data recorder that had both pre-crash and crash pulse data. The speed of the Sierra was reported as 109.4 km/h (68 mph) for each of the five second intervals prior to algorithm enable. For the first four one second intervals the throttle readout was 26% and the brake switch circuit status was off. In the final readout prior to AE, the throttle position dropped to zero and the brake switch circuit status changed to on. The cumulative ΔV curve peaked at 41.7 km/h (25.89 mph) at 110 ms and appeared to have flattened out. The maximum recorded ΔV was 42.0 km/h (26.11 mph) at 105 ms. Thus, assuming that the EDR provides reasonable speed estimates for the Sierra, the EDR provides the following additional data:

$$V_1 = 109.4 \text{ km/h}$$
$$\Delta V_{1X} = 42.0 \text{ km/h}$$

Using the above data, we can calculate the magnitudes of the total initial momentum of Vehicle 1 (m_1V_1) and the change in its longitudinal momentum ($m_1\Delta V_{1X}$):

$$m_1V_1 = 2731 \times 109.4 = 298{,}771 \text{ kg km/h}$$

$$m_1\Delta V_{1X} = 2731 \times 42.0 = 114{,}702 \text{ kg km/h}$$

Using the methodology outlined previously, we can draw a vector diagram for the momenta of the two vehicles involved in the collision (Figure 7):

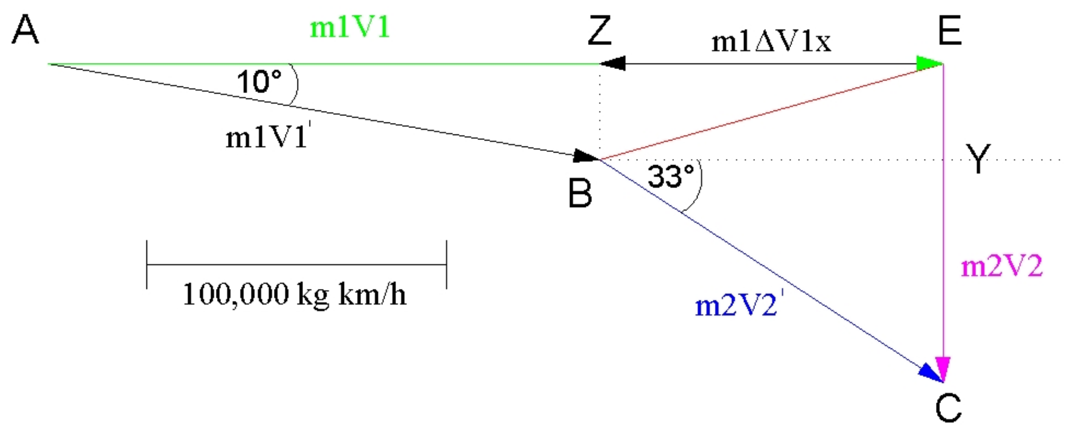

Figure 7 Momentum vectors - 2002 GMC Sierra (Vehicle1)/1999 GMC Jimmy (Vehicle 2)

From the scale diagram, the length of vector EC, the magnitude of the total initial momentum of Vehicle 2, is found to represent 106,945 kg km/h. Thus:

$$m_2V_2 = 106,\ 945 \text{ kg km/h}$$

$$V_2 = 106,\ 945 / 2096 = 51 \text{ km/h}$$

Also, the length of vector EY, the magnitude of the change in the longitudinal momentum of Vehicle 2 represents 32,456 kg km/h. Thus:

$$m_2\Delta V_{2x} = 32{,}456 \text{ kg km/h}$$

$$\Delta V_{2X} = 32{,}456 / 2096 = 15.5 \text{ km/h}$$

In the case collision, the Jimmy was also equipped with an EDR that provided only a measure of the vehicle's longitudinal ΔV. The maximum value reported by the EDR was $\Delta V_{2X} = 13.8$ km/h (8.56 mph). Thus, there is reasonable agreement between the calculated ΔV for the Jimmy and the value reported by the EDR.

2006 Hummer H3/1990 Ford F250/Side Impact

A 1990 Ford F250 pickup truck was eastbound and failed to come to a stop at a stop-sign controlled intersection. The left-front end of a northbound 2006 Hummer H3 utility vehicle struck the front-right side of the pickup. The Hummer was re-directed and came to rest in the ditch northeast of the point of impact (POI). The F250 spun out of the collision, coming to rest on the north side of the intersection. It was daylight, under clear skies, with dry asphalt pavement.

Tire marks, scrapes and gouges adjacent to the POI provided indications of the departure angles of the vehicles from the crash. Collision investigators identified the following parameters:

2006 Hummer H3	1990 Ford F250
$m_1 = 2267$ kg	$m_2 = 1873$ kg
$\theta_1 = 0°$	$\theta_2 = 90°$
$\theta_1' = 12.1°$	$\theta_2' = 14°$

The Hummer was equipped with the latest series of General Motors' SDM.s and provided the following additional information:

$$\Delta V_{1X} = 30.7 \text{ km/h (19.1 mph)}$$
$$\Delta V_{1Y} = 15.3 \text{ km/h (9.5 mph)}$$
$$PDOF_1 = 335°$$

From Equation 5, we can calculate the magnitude of the Hummer's total change in velocity (ΔV_1) and hence the magnitude of the total change in momentum ($m_1\Delta V_1$):

$$\Delta V_1 = \sqrt{(\Delta V_{1X}^2 + \Delta V_{1Y}^2)} = \sqrt{(30.7^2 + 15.3^2)} = \sqrt{(942.5 + 234.1)} = \sqrt{1176.6} = 34 \text{ km/h}$$

$$m_1\Delta V_1 = 2267 \times 34 = 77{,}078 \text{ kg km/h}$$

Using the value of 335° obtained from the EDR for the principal direction of force acting on Vehicle 1 ($PDOF_1$), together with the approach and departure angles for the two vehicles, we can construct the following momentum vector diagram:

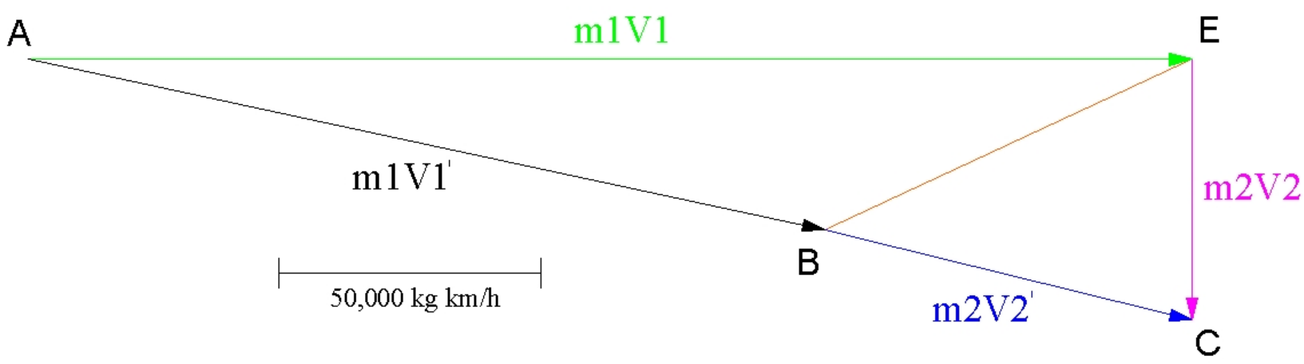

Figure 8 Momentum vectors - 2006 Hummer H3 (Vehicle 1)/1990 Ford F250 (Vehicle 2)

From the scale diagram, we can determine the magnitude of vector AE, the initial momentum of Vehicle 1 (m_1V_1), as 221,803 kg km/h, and that of vector EC, the initial momentum of Vehicle 2 (m_2V_2), as 49,992 kg km/h. Thus:

$$V_1 = 221{,}803 / 2267 = 98 \text{ km/h}$$

$$V_2 = 49{,}992 / 1873 = 27 \text{ km/h}$$

Given that we have previously calculated the magnitude of the total change in velocity for the Hummer (ΔV_1) as 34 km/h, we may use Equation 2 to determine the total change in velocity for the F250 (ΔV_2):

$$m_1 \Delta V_1 = | m_2 \Delta V_2 |$$

$$\Delta V_2 = m_1 \Delta V_1 / m_2$$

$$\Delta V_2 = 2267 \times 34 / 1873 = 41 \text{ km/h}$$

The Hummer's EDR also contained pre-crash data that indicated a vehicle speed of 117 km/h (73 mph) five seconds prior to AE, dropping to 113 km/h at one second prior to AE. At the latter point, throttle application was reported as zero with the brake switch circuit status being "Not applied". While there is no physical evidence of pre-impact braking on the part of the Hummer's driver, hard braking (0.7g) for approximately 0.5 s would have easily reduced the vehicle's speed to the 98 km/h obtained from our momentum analysis.

Damage analysis using WinCRASH [5], using vehicle-specific stiffness values for the Hummer and a force-balance approach to accommodate the side impact to the Ford F250, provided estimates for the vehicle ΔV's of 30 and 36 km/h respectively. These compare reasonably well with 34 km/h for the Hummer as indicated by the EDR, and 41 km/h for the F250 as computed using conservation of momentum. Trajectory analysis in WinCRASH indicated pre-impact speeds of approximately 91 km/h for the Hummer and 25 km/h for the Sierra, with ΔV's of 31 and 38 km/h respectively. A WinSMAC [6] simulation was also carried out. Setting the initial speed of the Hummer to 95 km/h and that of the F250 to 25 km/h provided a reasonable representation of the case scenario.

2002 Chevrolet Silverado/1999 Chevrolet S-10/Head-end Collision

A 2002 Chevrolet Silverado pickup truck was eastbound in the driving lane of an undivided, rural highway, approaching an intersection. It was a cloudy day and the asphalt-paved roadway surface was wet. The posted speed limit for the road was 100 km/h. The Silverado's driver pulled into the passing lane to overtake a slower vehicle. He then observed another vehicle ahead, stopped in this lane, and signaling to turn left. The Silverado's driver braked and steered to the left to avoid the stationary vehicle. The front of the Silverado came into a head-on collision with a 1999 Chevrolet S-10 pickup truck that was westbound on the highway.

The Silverado was equipped with an EDR that indicated a vehicle speed of 100 km/h (62 mph) at five seconds prior to AE with 79% throttle application. The throttle position briefly went to 82% at four seconds prior to AE as the vehicle accelerated to 101 km/h (63 mph). At three seconds prior to AE, and for all subsequent readouts, the throttle position was reported as zero, and the brake switch circuit status was on. At one second prior to AE the vehicle's speed was reported as 58 km/h (36 mph). The cumulative ΔV reached 47 km/h (28.96 mph) at 110 ms; however, the curve had not flattened out at this point.

The S-10 was also equipped with an EDR. This unit provided a record of cumulative ΔV, nominally for a period of 300 ms. The maximum ΔV was 90 km/h (55.95 mph) at 190 ms. The crash resulted in a power failure in the S-10's electrical system; however, this occurred late in the crash pulse (at 290 ms), after the curve had flattened out, and it did not affect the measurement of the maximum ΔV.

For the in-line crash, knowing the masses of the two vehicles, and using the maximum change in velocity recorded by the S-10's EDR (ΔV_2), Equation 2 can be used to estimate the change in velocity experienced by the Silverado (ΔV_1)

$$m_1 \Delta V_1 = -m_2 \Delta V_2$$

where: m_1 = 2759 kg (Silverado)
m_2 = 1557 kg (S-10)
ΔV_2 = 90 km/h

$$\Delta V_1 = -1557 \times 90 / 2759 = -51 \text{ km/h}$$

Note that, in the above analysis, we have implicitly used a sign convention where the initial velocity of the Silverado (Vehicle 1) is positive. In this crash, the S-10 experienced a reduction in its initial velocity to zero, and was then driven rearwards to its separation velocity, such that its change in velocity was positive (+90 km/h). The ΔV for the Silverado was calculated as being negative (-51 km/h), indicating that this vehicle was decelerated in the collision to a final speed that was 51 km/h less than its initial travel speed. The magnitude of the calculated ΔV for the Silverado is in reasonable agreement with the value recorded by the EDR (47 km/h), given that the latter was underestimated as a result of the system's memory limitations.

Due to the wet road, a precise point of impact for the crash was not determined, and hence run-out speeds for the vehicles were not determined. If we assume the initial speed of the Silverado to be that recorded by the EDR at one second prior to AE (58 km/h), and maintain the sign convention used above, the vehicle's separation velocity (V_1') would be given by:

$$\Delta V_1 = V_1' - V_1$$

$$V_1' = \Delta V_1 + V_1 = -51 + 58 = 7 \text{ km/h}$$

If the S-10 had the same separation velocity ($V_2' = V_1' = 7$ km/h), then its initial velocity would be given by:

$$\Delta V_2 = V_2' - V_2$$

$$V_2 = V_2' - \Delta V_2 = 7 - 90 = 83 \text{ km/h}$$

The two vehicles spun out of the collision, their rear corners making a secondary contact, before the vehicles came to rest on the wet roadway, close to the middle of the intersection. This suggests that the vehicle speeds on separation were not large, supporting the value of 7 km/h determined above. The estimated initial speed of the S-10, at 83 km/h, was below the posted speed limit for the road. It is not known if the S-10's driver applied the vehicle's brakes prior to impact. This vehicle's EDR did not have the capability to record any pre-crash information.

DISCUSSION AND CONCLUSIONS

Event data recorders have provided collision investigators with a new source of objective data that can be used to verify the results of conventional collision reconstruction techniques or, in the absence of complete field data, can be integrated into the calculation methodologies. This paper has shown how this might be undertaken where calculations involving the conservation of linear momentum are concerned.

Clearly, for angled crashes, the ability to construct a vector diagram for vehicle momenta is extremely valuable since this provides a direct pictorial representation of the vehicle headings in the collision and helps avoid any errors with respect to angular measurements and the associated calculations. Such a diagram also provides a ready measure of the change in momentum ($m\Delta V$) experienced by the vehicles in the collision, and thus yields a concrete link to the change in velocity for each vehicle that may be measured by their EDR's.

Earlier research has shown the data captured by EDR's, both in terms of change in velocity and travel speed, to be accurate [7,8]; however, the systems have also been shown to have some limitations [9]. In particular, the buffer that captures the crash pulse (as ΔV vs. time in 10 ms increments) has a finite size. Consequently, if a collision extends over a long time period, such that the number of data points exceeds the available space in the buffer, a portion of the cumulative ΔV will not be recorded and the reported value will be an underestimate. In addition, early EDR systems only capture the longitudinal component of the vehicle's ΔV. The vehicle speed, when available, is limited to the reading immediately prior to algorithm enable. While this is nominally reported as having occurred at one second prior to AE, the readout may actually apply to any time between one and zero seconds from AE. In addition, the system requires a finite, but unmeasured, time from the onset of the collision to the point at which the airbag deployment algorithm is enabled. This is generally the time for the vehicle to decelerate by approximately 2g. As a result of these unknown times, any pre-impact braking can affect the applicability of the reported speed. While investigators must be aware of such limitations, these are generally not so great as to disqualify the use of parameters derived from the EDR for use in a reconstruction.

In fact, one of the major benefits of EDR's is their ability to provide data that can be used as checks on a variety of values determined by conventional collision reconstructions techniques. In essence, these systems can provide one or more "instrumented" vehicles in a real-world crash and hence act as the basis for validation of "experimental" results. Conversely, the application of well-tried calculation methodologies can be used to confirm the validity of data obtained from EDR's.

In any given crash it is desirable to capture all of the available evidence that might be used for reconstruction purposes and use the best available data. When sufficient data are available to perform a momentum analysis, supplementary EDR data have been shown to be useful in the evaluation of the results obtained. However, where certain pieces of information are not available, we have also seen that parameters obtained from EDR's may be used to allow a momentum solution to be obtained. While there are many different scenarios that might be envisioned, the situations described in the present paper will commonly apply. Furthermore, the methodology can be extended as necessary to accommodate other collision types and available data sources.

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