DEVELOPMENT AND EVALUATION OF THE CRASH 2
PROGRAM FOR USE UNDER EUROPEAN CONDITIONS

Ian S. Jones and Peter W. Jennings

Oxford Road Accident Group,
Department of Engineering Science.
University of Oxford

INTRODUCTION

The Oxford Road Accident Group (ORAG) is currently compiling an accident data base to study injury mechanisms in road accidents and to explore the relationship between injuries and impact severities for car occupants. Accidents are investigated both on-scene and retrospectively in sufficient detail to enable accurate reconstruction of the collision environment.

Since one of the main objectives in collecting the data is to relate injury to crash severity it is imperative that accidents be reconstructed in a uniform and consistent manner. To this end emphasis has been put on reconstructing all applicable cases with the Calspan Reconstruction of Accident Speeds on the Highway (CRASH*) program. However although CRASH has been used extensively in the USA for accident reconstruction the accident environment in Europe is sufficiently different that the utility of the program in these conditions is unknown. This paper reports our experience in applying CRASH to 200 accidents attended on scene by the group, and a further 200 accidents investigated retrospectively by vehicle examination at garages. Results are presented which give the proportion of accidents that could be successfully CRASHed together with the reasons for not running CRASH.

Having established the frequency with which cases can be reconstructed the other consideration in terms of the program's utility is the reconstruction accuracy. This must depend upon how well the vehicle characteristics assumed in the program represent European vehicles. The most widely applicable part of CRASH is the damage analysis, used to obtain the velocity change (ΔV) of each vehicle. In calculating the energy absorbed in crushing the vehicle structure the damage analysis assumes a linear force versus crush relationship as defined by two stiffness coefficients. To take account of variations in vehicle size and impact type, coefficients are specified for six vehicle sizes for each of three impact types, front, side and rear.

---

* The CRASH 2 version of the program is used throughout.

For the larger vehicle size categories adequate test data has been available to the program's authors to enable them to obtain accurate coefficients; however most European cars fall into the three smaller size categories for which the stiffness coefficients are based on much more limited data (1).

A statistical optimisation technique has been used to obtain new stiffness coefficients for frontal impacts for the minicar, subcompact and compact size categories. The test data has been obtained from a recent series of block and mobile barrier tests involving a total of 42 usable frontal impacts, with ΔV's ranging from $\sim$15 mile/h (24 km/h) to $\sim$40 mile/h (64 km/h). The resultant coefficients show a significant improvement in accuracy, but the data suggest an energy (or crush) dependance of the coefficients themselves. The coefficients have therefore been modified in an attempt to reach the best compromise for all frontal impact severities.

The trajectory analysis of CRASH has also been modified to allow the user to input a yaw angle for each vehicle if desired. This will obviously increase both the accuracy of the trajectory analysis and the range of cases to which the program may be applied.

ACCIDENT DATA DESCRIPTION

In compiling our accident data base we are endeavouring to collect a representative sample of car collisions, representative that is in terms of impact type and severity (collisions with pedestrians, cycles and motorcycles are excluded). The core of our sample consists of accidents investigated on-scene with call out by the local Ambulance Service. These accidents are obviously biased towards injury and so to fill the 'no injury' gap we also collect those accidents reported to the Police but not involving Ambulance call out on a 48 hr follow-up basis. To ensure uniform selection, a criterion that the vehicles had to be sufficiently damaged as to require towing from the scene was adopted.

RECONSTRUCTION OF ON-SCENE CASES

To date, 200 on-scene cases have been processed and of these 124 or 62.0% of the sample have been run through the CRASH program. To gauge the utility of the program Table 1 provides a breakdown of the reasons for those cases not run through CRASH.

It can be seen that of the 76 (38.0%) accidents that could not be CRASHed, 55 involved accident situations which violate CRASH assumptions; 13 (6.5%) were sideswipes such that the vehicles did not reach a common velocity, 28 (14.0%) involved loss of control or rollover, 4 (2.5%) involved multiple vehicles and there were 9 (4.5%) miscellaneous accident configurations e.g. stolen vehicle impacted rear of towing vehicle. For the remaining 21 (10.5%) accidents one or more vehicles were not examined in sufficient detail to get damage measurements to run CRASH. This usually resulted from the vehicle being moved out of the area immediately following the accident. Assuming that this loss of data could be eliminated the highest proportion of car accidents that one could expect to be CRASHable is about 70-75%.

Since our interest is principally in determining ΔV to relate crash severity to injury severity, cases shown as CRASHed in Table 1 refer to cases where

TABLE 1

On-Scene Data - Reasons for not running CRASH

Reasons for No CRASH Run	No. of Accidents	%
Side Swipe	13	6.5
Loss of Control/rollover etc.	28	14.0
Multiple	5	2.5
Vehicles not examined	21	10.5
Others	9	4.5
Total NOT CRASHED	79	38.0
CRASHED	124	62.0
Total: ACCIDENTS	200	100.0

it was at least possible to run the damage analysis of the program. For a complete run of CRASH, rest and impact positions have to be known and the spin out trajectories must not violate assumptions made in the SPIN2 algorithm. For the on-scene cases, that could be run on CRASH, 33% had rest and impact positions with acceptable trajectories such that a full run of CRASH could be made; there were a further 9% of cases where rest and impact positions were known but these cases had spin out trajectories that violated SPIN2 assumptions e.g. vehicle ended up in ditch, struck a kerb etc. Comparing these figures with those from a previous U.K. study (2), which looked at the utility of using CRASH to reconstruct on-scene cases, the earlier results suggested that in 4% of all cases a full CRASH run was possible and in 38% of cases a damage only run. The present reconstruction rates are much higher at 20% (33% of 62%) for full runs and 62% for damage only runs. These differences are partly attributable to different collection criteria, the present study looks at injury accidents, where the severity is usually sufficient to immobilise the vehicles, whereas the previous study was based on all accidents notified to the police, such that a larger proportion of vehicles would have been moved from their rest positions prior to the arrival of the investigation team.

RECONSTRUCTION OF RETROSPECTIVE CASES

Two hundred of the retrospective cases have been processed and of these 105 or 52.5% have been successfully run through CRASH. Table 2 gives a breakdown of the reasons for not running the program. Of the 95 cases that could not be run 78 involved accident situations which violate CRASH assumptions; 18 (9.0%) were sideswipes, 49 (24.5%) involved loss of control or rollover, 3 (1.5%) involved multiple impacts and there were 8 (4.0%) miscellaneous accident configurations. For the remaining 17 (8.5%) accidents one or more vehicles were not examined, primarily the result of vehicles being moved from the garage or scrapped before our follow-up.

Comparison with the corresponding figures for the on-scene cases in Table 1 show that the proportion of lost data appears to be about the same. This is not surprising in that our time to follow-up for on-scene cases and retrospective cases is approximately the same. The main differences between the Tables are in the loss of control/rollover and sideswipe accidents; both appear more frequently in the retrospective cases and can be explained by the bias of these cases towards non injury accidents i.e. both types of accident tend to be low severity collisions and would therefore feature predominantly in the retrospective cases.

TABLE 2

Retrospective Data - Reasons for not running CRASH

Reasons for No CRASH Run	No. of Accidents	%
Side Swipe	18	9.0
Loss of Control/Rollover etc.	49	24.5
Multiple Accident	3	1.5
Vehicle Not Examined	17	8.5
Others	8	4.0
Total NOT CRASHED	95	47.5
CRASHED	105	52.5
Total: ACCIDENTS	200	100.0

COMPARISON WITH U.S. DATA

Since the CRASH program was originally written for U.S. conditions it is instructive to compare our success rate for reconstruction with that in the U.S. For comparison purposes the National Crash Severity Study (NCSS) data (3) is probably the most suitable from the point of view of similar collection criteria. In this study police reported tow-away accidents are collected to a set sampling plan and investigated on a follow-up basis. The CRASH program is applied to each accident to calculate velocity change. Results (4) suggest a successful reconstruction rate of approximately 50% although a more detailed analysis of a sample of these accidents (5) gives a slightly higher rate of 64%. In that analysis out of a total of 49 cases reviewed 18 could not be CRASHed; of these 18 there were 6 (12%) which lacked sufficient vehicle information, 2 (4%) were side swipes, 5 (10%) were rollover and 5 were other miscellaneous accident configurations.

REFINEMENT OF FRONTAL DAMAGE ANALYSIS

A recent series of frontal and side impacts performed for the Transport and Road Research Laboratory has been analysed; the cars have been measured by ORAG to obtain all the necessary damage data for CRASH reconstruction, and the integral of the accelerometer traces (uncorrected for vehicle rotation during impact) analysed to obtain ΔV for each vehicle. Further details of the tests are given in (6).

The cars were divided into size categories as follows:-

MINICAR	SUBCOMPACT	COMPACT
VW Golf	BL Marina	BL Princess
Fiat 133	Vaux. Chevette	
Renault 5	Colt Lancer	
Datsum Sunny	Chrysler Alpine	
Ford Fiesta	Ford Escort	

Each model of car was subjected to the following tests.

(1) A full frontal block impact at about 40 mile/h (64 km/h)
(2) A 30% overlap block impact at about 30 mile/h (48 km/h)
(3) A rigid mobile barrier impact at about 22 mile/h (35 km/h)
(4) A mobile barrier side impact at about 22 mile/h (35 km/h)
(5) A 30 degree angled barrier frontal impact at about 30 mile/h (48 km/h).

Because the only available test data for side impacts is all in one narrow speed range, no suitable coefficients could be found for CRASH without assuming the general shape of the crush/ΔV graph, hence the side impact data has not been given in this report.

One model of car tested does not appear in our data because it is of fibreglass construction, which has rather different crush characteristics to the other cars listed. Also two of the minicar cases were found to be unsuited to the study, leaving a total of:-

18 minicar tests involving	5 car models
20 subcompact tests involving	5 car models
4 compact tests involving	1 car model

For the simple case of a full width perpendicular car versus block test, the damage algorithm used by CRASH is

$$E = \tfrac{1}{2}m\Delta V^2 = L(AC+BC^2+G)$$

where
E = energy of deformation
m = vehicle mass
ΔV = velocity change due to impact
L = width of damaged region
C = function which represents the crush
A,B = crush coefficients
$G = A^2/2B$

Using the generalised expression for the energy of deformation a statistical technique (see Appendix) was applied to the data for each size category, to provide the 'best fit' values for A and B; the results are shown in Table 3. The coefficient 'G' which is a combination of the two main coefficients, may be interpreted to give a 'threshold ΔV', i.e. the ΔV below which a car suffers no permanent damage. For a typical European car (assuming no energy absorbing device in the bumper) for a full frontal block impact one expects the threshold to be of the order of 2-3 mile/h (3-5 km/h): but the coefficients derived from this data give thresholds of 24.7 mile/h (39.7 km/h) for minicars, 14.8 mile/h (23.8 km/h) for subcompacts and 12.5 mile/h (20.1 km/h) for compacts. These thresholds are clearly too high although such an effect is not unexpected because no test data has been used below a ΔV of 15 mile/h (24.2 km/h). Extrapolation outside the test data range is always difficult, especially into the low severity region where the car structure behaves in a more complex way than the 'lumped mass' model of CRASH which is more suited to high ΔV impacts. However a model, albeit approximate, is desirable in the low ΔV region because the threshold ΔV for injury accidents is believed to be in this region.

There are two possible ways of overcoming this problem. Firstly some form of ΔV dependance may be put into the stiffness coefficients (or a separate set of low severity coefficients used) but unfortunately no suitable test data has been available to enable quantification of this low ΔV dependance. The second possibility is to force the regression line closer to the origin by a weighting factor applied to the regression data, the effect of which is to treat the threshold for damage as a data point itself. The amount of weighting applied does not affect the data, only the proximity of the regression line to the origin and therefore the threshold ΔV. This has been done, and the results are also shown in Table 3.

This weighting factor is equivalent to including in the data a threshold of damage that is believed to be around 2 mile/h (3 km/h). The effect of this weighting is to reduce the threshold ΔV's to: 8.7 mile/h (14.0 km/h) for minicars, 7.0 mile/h (11.3 km/h) for subcompacts and 5.4 mile/h (8.7 km/h) for compacts.

Table 3 - CRASH 2 Stiffness Coefficients

Car Category		Standard Coefficients	New Coefficients Unweighted	New Coefficients Weighted for Threshold
Minicars	A	85.4	453.0	327.0
	B	64.0	14.0	58.0
Subcompacts	A	94.9	604.0	369.0
	B	71.1	57.0	96.0
Compacts	A	154.6	500.0	282.0
	B	69.6	44.0	76.0

These thresholds are still higher than the desired levels, but the modified coefficients represent the best compromise that can be obtained with a linear model between a realistic threshold and a good fit to the test data. The technique employed here has little effect on high severity ΔV accuracy, but use of the coefficients weighted for threshold of damage tends to lead to an underestimate of the true ΔV in the 15 mile/h (24.2 km/h) range.

The new weighted coefficients show a significant improvement in accuracy of reconstruction for the minicar and subcompact size categories as shown in Figures 1 and 2; the data for these figures are given in Tables 4 and 5. The degree of scatter for both categories is also slightly improved although this is likely to be limited by the natural variation in model types and impact configurations. For minicars the new coefficients give all but 4 results to within 10 mile/h (16 km/h), as opposed to the standard coefficients which give 9 results outside this band; the corresponding figures for subcompacts being 1 and 4 respectively. Unfortunately only one model of car was available for the compact category; therefore a generalisation of the results for this category will not be possible until further car models have been added to the data.

These new coefficients represent the optimum fit to the range of data available: if different models of cars, or tests in different speed ranges become available, then of course further refinements will become possible. However the range of cars and of impact severities used in this paper appears to be a good reflection of the European accident environment.

For accident reconstruction purposes the accuracy of the new coefficients must be known for car-car collisions. We are currently testing the new coefficients on a series of car-car collisions involving European vehicles each with a ΔV of about 30 mile/h (48 km/h). Preliminary results indicate that in this ΔV region the accuracy with the new coefficients is not significantly different. Unfortunately car-car tests are not available at lower ΔV's so it has not been possible to confirm the improvement in accuracy, for car-car collsions, that the low ΔV car-barrier tests suggest.

REFINEMENT OF TRAJECTORY ANALYSIS

Limitations in the trajectory analysis have previously been noted (2,7). Some of these (such as the inability to accommodate sideswipe collisions, kerb strikes and wheels leaving the ground) cannot be accommodated within the existing program algorithms. However an assessment of the analysis has revealed two developments which users may insert without difficulty. The first of these concerns the error discovered in START2 by the authors of (7). This error is an ambiguity in the algorithm as to the 'end of skidding' position for those trajectories where a curved path is present. Their correction requires a further modification in that the values inserted in SPIN2 for XEND, YEND, should be multiplied by 12. The second development is to modify the program to accommodate yaw angles for either vehicle on impact. Our on-scene studies have revealed several cases where pre impact skid marks clearly indicate the presence of yaw angles; if they are present CRASH will not correctly give the vector sum of separation velocities and ΔV from damage (to give the impact speed for co-linear collisions) nor will it correctly resolve the momenta of the vehicles to give the impact speeds and ΔV components (in intersection collisions), because the momenta will be resolved along the car heading angles, not their velocity heading angles. A version of CRASH has been developed by ORAG which hands the correct values from START2 (the main trajectory analysis coding) to OBLIQE (the subroutine which applies the conservation of linear momentum) and which also

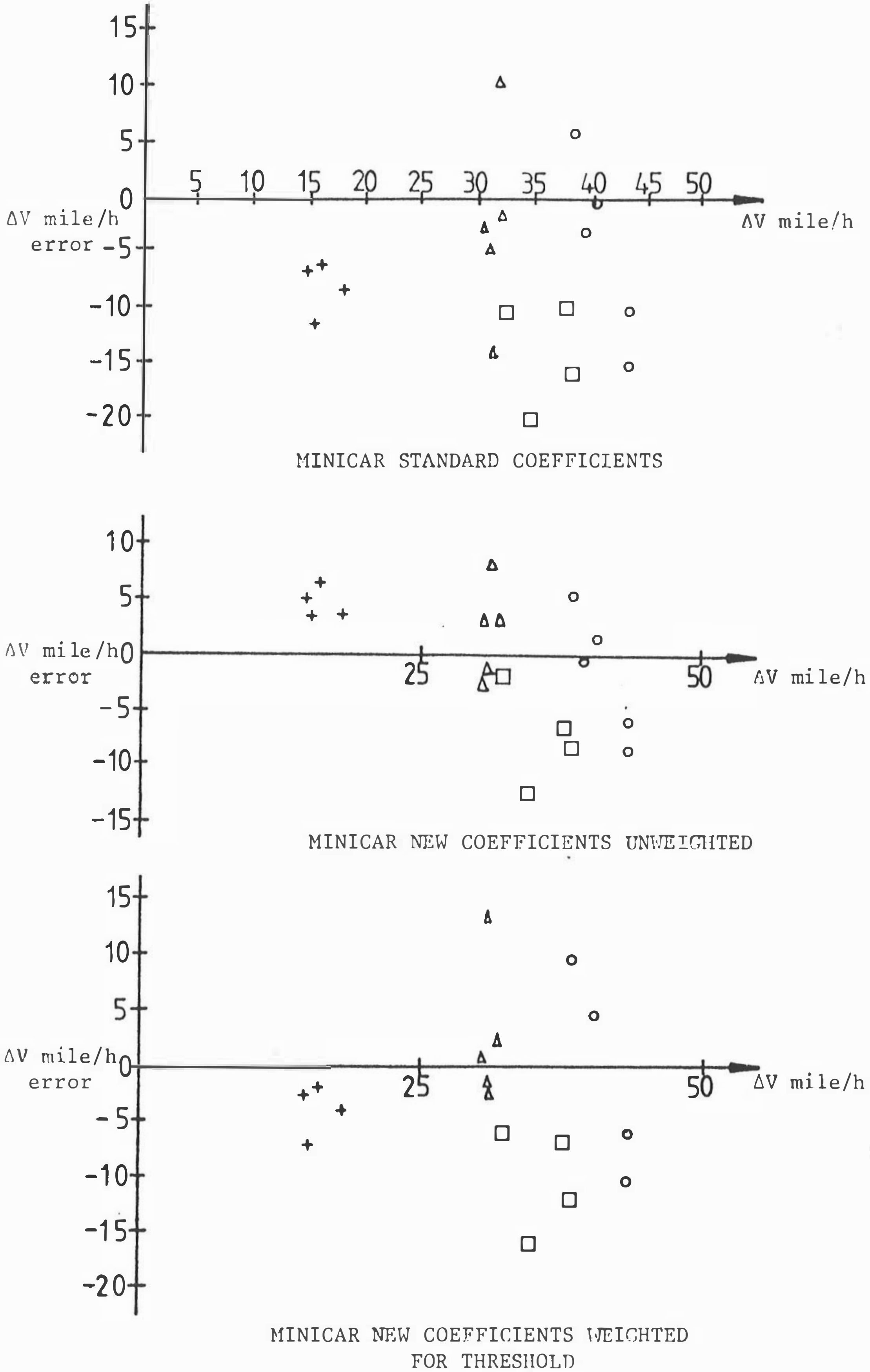
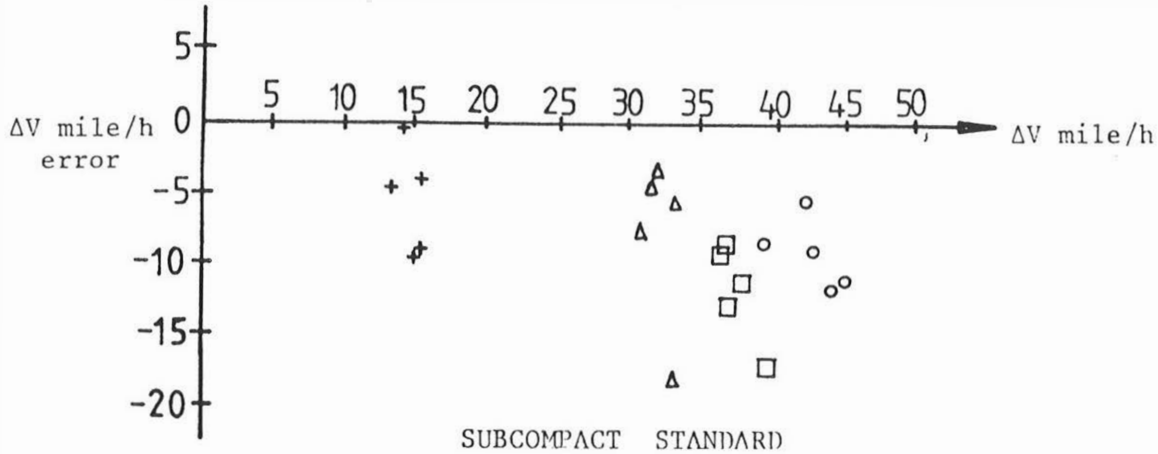
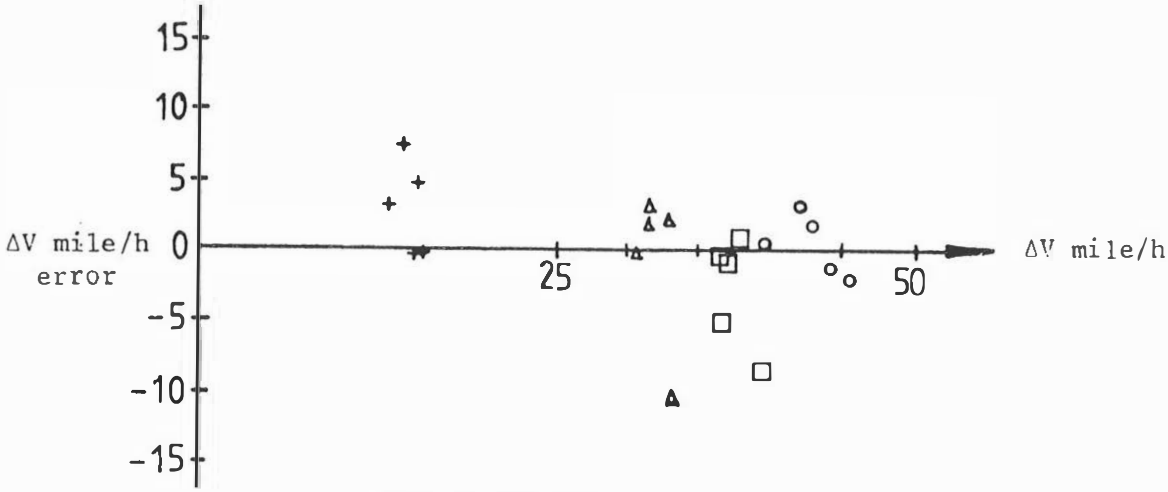


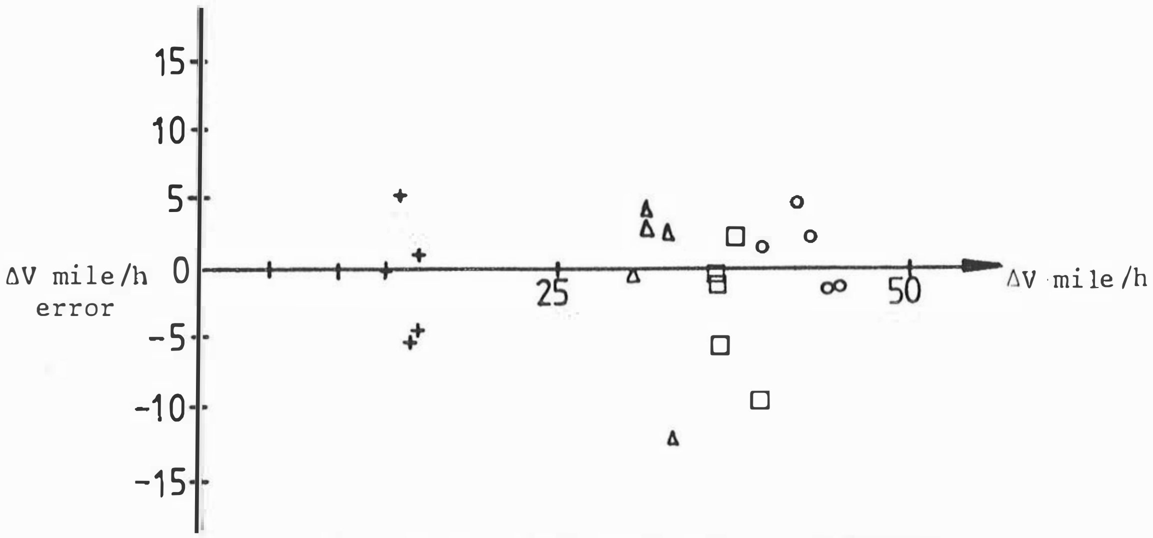
Figure 1 - Error in ΔV vs ΔV for Standard and Revised Stiffness Coefficients - Minicars



SUBCOMPACT STANDARD
COEFFICIENTS



SUBCOMPACT NEW COEFFICIENTS



SUBCOMPACT NEW COEFFICIENTS WEIGHTED
FOR THRESHOLD

Figure 2 - Error in ΔV vs ΔV for Standard and Revised Stiffness Coefficients - Subcompacts

Table 4 - Comparison of Measured and Predicted ΔV's
Using Standard and Modified Coefficients
for the MINICAR Category

MINICARS		ΔV From Accelerometers	Predicted ΔV's		
			New Coefficients Unweighted	New Coefficients Weighted for Threshold	Standard Coefficients
Full Block	FF1	40.4	41.7	44.6	40.1
	DS1	43.5	37.4	37.3	32.6
	FT1	38.5	42.5	48.2	44.2
	VG1	39.1	38.1	40.3	36.0
	RN1	43.5	35.7	33.4	28.4
Offset Block	FF2	30.1	34.0	31.6	27.3
	DS2	30.7	29.0	29.1	25.7
	FT2	31.0	39.1	44.4	41.3
	VG2	31.7	35.0	34.5	30.4
	RN2	31.1	30.4	28.7	17.3
Mobile Barrier	FF3	18.2	21.7	14.2	9.8
	DS3	14.9	19.7	12.2	8.1
	FT3	14.9	-	-	-
	VG3	15.9	21.2	13.9	9.6
	RN3	15.2	18.2	8.2	3.8
Angled Block	FF5	32.3	29.9	26.0	21.8
	DS5	37.6	30.9	30.9	27.3
	FT5	39.1	-	-	-
	VG5	38.5	29.8	26.6	22.6
	RN5	34.8	26.0	19.0	41.6

Table 5 - Comparison of Measured and Predicted ΔV's Using Standard and Modified Coefficients for the Sub-Compact and Compact Categories

		ΔV From Acceler-ometers	Predicted ΔV's		
			New Unweighted Coefficients	New Coefficients Weighted for Threshold	Standard Coefficients
SUBCOMPACTS					
Full Block	FP1	42.9	44.5	45.0	34.7
	MM1	44.2	42.3	42.4	32.5
	VC1	39.5	40.4	40.4	31.0
	CL1	45.1	42.8	43.3	33.4
	CA1	42.3	45.5	47.1	36.8
Offset Block	FP2	30.5	30.0	29.8	22.8
	MM2	32.9	34.7	35.5	27.6
	VC2	31.1	32.8	33.9	26.5
	CL2	32.9	22.8	20.4	14.7
	CA2	31.4	34.1	35.6	28.0
Mobile Barrier	FP3	15.2	19.8	16.3	11.1
	MM3	15.2	15.1	10.5	6.2
	VC3	14.9	14.6	9.5	5.2
	CL3	14.3	21.8	19.4	13.9
	CA3	13.3	16.6	13.2	8.8
Angled Block	FP5	36.7	31.6	31.0	23.6
	MM5	36.4	35.1	35.1	26.9
	VC5	37.6	38.4	39.9	31.2
	CL5	39.4	30.7	29.6	22.2
	CA5	36.4	34.8	35.9	28.0
COMPACTS					
	LP1	37.9	41.7	43.3	39.3
	LP2	32.8	27.6	28.1	25.5
	LP3	13.2	16.2	13.3	11.2
	LP5	35.3	38.2	39.6	36.0

resolves all velocities correctly when yaw is present. The development requires only minor modifications to the QUIZ, START2 and PRINT subroutines.

CONCLUSIONS

Program Utility

- Approximately 62% of the on-scene accidents could be reconstructed with damage only runs of the CRASH program; another 10.5% were CRASHable but had insufficient data; and 20% of the cases were either side swipe or loss of control/rollover accidents and could not be crashed.

- Of the 62% of CRASHable on-scene cases 33% had rest and impact positions and suitable trajectories for a complete CRASH run to be made; a further 9% of these cases had rest and impact positions specified but had post impact trajectories violating CRASH assumptions.

- Approximately 52% of the retrospective accidents could be reconstructed with damage only runs of the CRASH program; another 8.5% were CRASHable but had insufficient data; and 33.5% of the cases were either side swipe or rollover accidents and could not be CRASHed.

- Comparison with the National Crash Severity Study data, which is representative of U.S. conditions, shows that our success rate for CRASH reconstructions in follow-up investigations is similar i.e. about 50%.

Program Development

- A total of 38 car tests have been used to obtain more accurate frontal crush stiffness coefficients for the minicar and subcompact categories. A further 4 tests have been used to explore the accuracy of the compact category. The suggested new coefficients are presented, together with a comparison of the standard coefficients on a test by test basis.

- Difficulties in obtaining a realistic threshold ΔV for the onset of crush deformation have necessitated weighting the optimisation techniques, leading to a more realistic threshold, but a slightly reduced goodness of fit to the individual data points.

- The trajectory analysis of CRASH has been modified to accommodate yaw angles on impact, giving increased accuracy and utility of the algorithm.

ACKNOWLEDGEMENTS

The authors would like to thank Mary L. Medlan, Kathie Lawrence and Steven Humm of the Clinical Team and Andy Tippett of the Engineering Team for all their help and assistance in collecting and processing the accident data. Thanks also to the Thames Valley Police and Oxfordshire Ambulance Authority without whose cooperation we would not be able to collect the accident data. We gratefully acknowledge the Transport and Road Research Laboratory for funding the project and for providing test data from a series of collisions performed for them by the Motor Industry Research Association.

REFERENCES

1. McHenry, R. R., 'Yielding-Barrier Test Data Base-Refinement of Damage Data Tables in the CRASH program' Calspan Report ZR-5954-V-1 December 1976 Contract No. DOT-HS-6-01372.

2. Staughton, G. C. and Jennings, P. W., 'Application of the Calspan CRASH Program under European Conditions' TRRL Supplementary Report 528: Crowthorne, 1979 (Transport and Road Research Laboratory).

3. Kahane, C., Smith, R. and Tharp, K., 'The National Crash Severity Study' Report on the Sixth International Technical Conference on Experimental Safety Vehicles. Pub. No. DOT-HS-802-00. NHTSA Washington, D.C., 1976.

4. Partyka, S. C., 'Fatal Accidents in the First Fifteen Months of the National Crash Severity Study'. Proceedings of 23rd Conference of the AAAM Louisville, Kentucky, Oct. 1979.

5. Jones, I. S., and Baum, A. S., 'Accident Investigation Methodology to Assess the Role of Vehicle Braking in Highway Safety' Calspan Report ZQ5779-U-1. Contract No. DOT-HS-5-10230.

6. Neilson, I. D., Penoyre, S., and Petty, S. P. F., 'Improved Test Procedures for Frontal Impact'. The 7th International Technical Conference on Experimental Safety Vehicles. Paris 1979.

7. Jones, I. S. and Baum, A. S. 'Research Input for Computer Simulation of Automobile Collisions Volume IV Stages Collision Reconstructions'. Final Report December 1978. Report No. ZQ-6057-V-6. Contract No. DOT-HS-7-01511.

APPENDIX

The generalised algorithm for obtaining ΔV_i for an inelastic collision between vehicles i and j is

$$\Delta V_i = \sqrt{\frac{2\gamma_i(E_i+E_j)}{m_i\left(1+\frac{\gamma_i m_i}{\gamma_i m_j}\right)}} \tag{1}$$

where $\gamma = \frac{h^2}{h^2+k^2}$

h = radius of gyration
k = offset of principle force from centre of mass for vehicle
m = mass
E = deformation energy

and in CRASH the value of E_i for vehicle i

$$E_i = L_i\left(Af(c)+Bf(c^2)+\frac{A_i^2}{2B_i}\right)(1 + \tan^2\alpha) \tag{2}$$

where L = width of damaged region
f(c) = function describing the crush profile
$f(c^2)$ = function describing the first moment of the crush profile
α = angle of principal force from perpendicular
A,B = crush coefficients

For each test used in this report the test vehicle is vehicle 1, and the block or barrier is vehicle 2, $E_2 = 0$.

Rearranging (1) and (2)

$$\left(\frac{m_1\left(1+\frac{\gamma_1 m_1}{\gamma_2 m_2}\right)}{2L\gamma_1(1+\tan_1^2\alpha)}\right)^{\frac{1}{2}} \Delta V = Af(c) + Bf(c^2) + \frac{A^2}{2B} = \varepsilon\text{, say}$$

Since all terms on the left hand side are known, an optimisation technique may be used to find A and B, provided at least two test results are available.

A program was written using the National Algorithm Group mathematical computer package NAG7, program E04FDF to perform the optimisation by minimising the function

$$Q = \sqrt{Af(c)+Bf(c^2)+\frac{A^2}{2B}} - \varepsilon$$ for the given data in each size category.