VEHICLE STABILITY - MECHANICS OF TRUCK ROLLOVER

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SYNOPSIS

Heavy vehicles with high centres of gravity are prone to rollover accidents. A combination of tilt testing of a range of articulated tankers, together with a computer model of the rollover process, has been used to determine means of improving stability. Parameters including lateral load transfer at each axle group, deflections of the sprung and unsprung parts of the suspensions and movement at the fifth wheel coupling will be presented. The effects of suspensions, couplings and tyres on the rollover limit will be discussed. It is concluded that centre-of-gravity height, track width and suspension characteristics are the main factors influencing stability. Means of implementing the results are discussed, including a Users' Guide to suspension matching and vehicle design improvements. Further research to be carried out involving full-scale dynamic testing with outriggers fitted will be discussed.

1. INTRODUCTION

Size and weight limits of heavy trucks have come under close scrutiny in recent years and one outcome of increases in gross weight, together with a large height to width ratio, is a tendency to rollover.

Articulated trucks pose a particular problem because they are the heaviest and tend to have the highest centres of gravity, and because drivers lack good motion feedback from the semi-trailer. A recent international enquiry (1)** showed that overturning frequencies range from 4 to 15 per cent of heavy vehicle

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** Numbers in parentheses designate references at end of paper.

accidents, the higher percentages occurring in countries where the national fleet contains a high proportion of articulated vehicles.

In Australia, articulated vehicles with tandem drive axles and triaxle trailer axles pre-dominate on line-haul routes and the maximum height limitation (4.3 m) is fairly liberal. Truck stability is therefore an important issue in the examination of size and weight limits. It has also been a matter of concern to the transport industry for some time.

The Australian Road Research Board's (ARRB's) study of truck stability has been strongly supported by the transport and vehicle manufacturing industries, as well as the Federal Office of Road Safety.

The research has taken two parts - tilt testing of a range of vehicles and computer modelling of the rollover process. These aspects will be covered only briefly here - they have been fully reported in (2). The present paper will concentrate on the results, implications and some applications of the research.

ARRB has also been studying the road damaging effects of trucks, particularly the effects of suspensions and tyres. It is not possible to consider improvements in the road efficiency of suspensions without considering roll stability at the same time. Tyre effects, including the use of wide single tyres, are also an important consideration.

2. TILT TESTING

Detailed study of the vehicle behaviour up to the point of rollover is difficult in dynamic tests. It is necessary to carry out static tests on a tilt deck. This technique permits examination of the role of suspension and fifth wheel coupling factors, and the development of a mathematical model.

2.1 Tilt Deck

The principal instrument in the series of static stability tests performed is a tilting platform. It consists of an essentially flat steel deck pivoted longitudinally along one edge, while the other can be lifted by four hydraulic cylinders in simultaneous motion. The platform can accommodate vehicles up to 20 m long and 40 tonne weight. The maximum inclination to which it can be raised is 40 degrees relative to the horizontal position. This inclination is measured by two linear transducers positioned fore and aft of the platform and connected between ground and the deck.

The tangent of the inclination angle - which is also the ratio of the vehicle's lateral force to its normal load, relative to the deck surface - is used to simulate the lateral acceleration, in terms of g (gravitational acceleration), applied to the vehicle while making a turn on the road. The vehicle is prevented from sliding by tyre side chocks and is restrained from accidental rollover by chains between the deck and axles and body (the chains offer no roll resistance during the test).

Those sections of the deck which fall underneath the vehicle's left side tyres consist of three load measuring platforms. The measurements from these load platforms serve two purposes. Firstly, they indicate most accurately the threshold of wheel lift. Secondly, they are used in calculating the various moments exerted on the tyres, suspensions, body and fifth wheel etc. as the vehicle rolls in response to lateral force.

2.2 Suspension Measurements

Considering the vehicle in the roll plane at an axle group, there are two substantial masses: the unsprung mass (axles and tyres) and the sprung mass (trailer or tractor body). They are capable of moving in the vertical and horizontal directions as well as of rolling. Thus, six co-ordinates and hence, six transducers are needed to define the vehicle completely. Four vertical linear transducers and the two lateral transducers are used to measure these co-ordinates. A lower lateral arm is attached across all axles in the group and an upper lateral arm is attached to the vehicle chassis. The following variables are computed from the six transducer readings:

(a) vertical and horizontal movements of axle centre relative to ground,

(b) vertical and horizontal movements of suspension top centre relative to axle,

(c) roll angle of axle relative to ground, and

(d) roll angle of suspension relative to axle.

At the drive axle group the trailer body and the tractor chassis are connected by the fifth wheel which itself is capable of deflecting and separating from the skid plate. The angles between the tractor chassis and fifth wheel and between the fifth wheel and skid plate were also measured.

2.3 Test Vehicles

Most test vehicles were tankers on loan from member companies of the Australian Institute of Petroleum. Selection of the test vehicles was largely based on suspension types and, in all, fourteen combinations were tested. The intention was to cover the most common suspension types seen on Australian roads, as well as to include the types already tested for dynamic road loading (3). The essential types to be covered were, on tractors:

walking beam

single point

torsion bar

four-spring

and, on trailers:

six-spring triaxle

four-spring tandem

air tandem

air triaxle.

These suspension types are illustrated in Fig. 1.

2.4 Results

The tilt test allows the characteristics of tyres, suspensions and fifth wheel couplings to be determined. Fig. 2 shows the roll compliance of the tyres, in terms of the roll angle developed at the axle as a function of the applied overturning moment. The relationship is typically quite linear. Fig. 3 shows the suspension behaviour. Unlike the tyres, most suspensions are non-linear and they vary considerably in their roll compliance characteristics. One noticeable feature in some truck suspensions is a rapid increase in roll compliance as the springs go from a state of compression into a state of tension. The presence of anti-roll devices noticeably reduces the roll compliance in some suspensions. Fig. 4 illustrates the fifth wheel behaviour, both in terms of compliance of the fifth wheel and its mountings, and in terms of the separation which develops between the fifth wheel and the trailer skid plate (i.e. when the trailer kingpin is placed in a state of tension).

The tilt test also allows the rollover process to be studied. This is represented by plotting the degree of lateral load transfer at the drive axle group against that at the trailer axle group. Fig. 5 shows a typical result and illustrates the general tendency for the trailer wheels to lift (i.e. 100% load transfer) before the tractor wheels. This is because, in general, trailer suspensions are less roll compliant than tractor suspensions and they are less laden on a per-axle basis. The point of trailer wheel lift, and its attendant tilt deck angle and lateral acceleration, is defined as the rollover threshold.

Further details of the characteristics of tyres, suspensions, fifth wheels and chassis are given in (2). These are used in the computer model. For the vehicles tested, rollover occurred in the range 0.35 g to 0.45 g. Such a rollover threshold places these vehicles in the category of high risk of rollover in a single vehicle accident (4). The reasons for the tendency to rollover are best understood through the computer model, where one factor may be studied holding all others constant.

3. COMPUTER MODEL

A model for the simulation of the static lateral stability of articulated vehicles was developed. It was verified using experimental data from the tilt testing program. The model is fully described in (2).

The most important factors are:

(a) Increasing the trailer centre-of-gravity height by 21 per cent, (from 1.95 m to 2.35 m) reduces the wheel lift lateral acceleration by 26 per cent, a predictably strong effect.

(b) Increasing the trailer axle track width by 11 per cent (equivalent to replacing conventional dual tyres with wide singles while maintaining a 2.4 m external tyre measurement) leads to a 10 per cent increase in wheel lift lateral acceleration.

(c) The drive axle suspension compliance was reduced in steps of 10 per cent up to 60 per cent. An optimum result was obtained at a compliance reduction of 40 per cent, where the wheel lift lateral acceleration had increased by 9 per cent.

(d) Decreasing the drive axle load by 14 per cent causes a 5 per cent increase in trailer wheel lift lateral acceleration.

(e) Increasing the trailer sprung mass by 50 per cent (from 20 t to 30 t) causes a 13 per cent reduction in wheel lift lateral acceleration. This effect is cancelled if the unsprung mass increases equally.

(f) Elimination of a maximum amount of fifth wheel separation (1.3°) results in an increase of 4 per cent in wheel lift lateral acceleration.

4. IMPROVING TRUCK STABILITY

There are two potential areas where improvements in stability may be sought:

(a) selection and matching of tractors with trailers, and

(b) vehicle design.

To assist fleet operators a Users' Guide (Fig. 6) has been published (2) which indicates that only two of 35 combinations considered are rated "A" for stability. Selection and matching based on suspension type is therefore very important.

Recommendations for vehicle design improvements have also been made, as follows:

(a) All means of reducing centre-of-gravity height should be fully exploited because the wheel lift lateral acceleration increases by almost 0.03 g for every 100 mm reduction in effective centre-of-gravity height. Average centroid heights varied by 200 mm among the vehicles tested.

(b) Change-over from dual tyres on the trailer to wide singles at the same outside lateral distance is one of the most effective single design measures. Widening of the spring base has a similar effect. On the other hand, fitting of wide single tyres to the drive axles will have no effect on stability unless the spring base is widened. This is an important distinction : on the trailer it is the widening of the ground contact track width and spring base which counts, while the reduced sprung mass roll compliance counts on the prime mover.

(c) The model predicts a substantial benefit of adding anti-roll bars to the drive axle suspension. An almost 10 per cent improvement in wheel lift lateral acceleration results from the addition of optimally-rated torsion bars to the standard vehicle. This might be the only design choice to increase the drive axle suspension roll stiffness as currently-available drive suspensions already have normalised compliance per axle comparable to that of trailer suspensions.

(d) Elimination of fifth wheel separation will lead to a small improvement in wheel lift lateral acceleration.

(e) Elimination of suspension unit slack in going from compression into tension results in a small improvement in wheel lift lateral acceleration.

A standard test for certifying stability to a level of 0.4 g has been proposed by ARRB, using the tilt deck. This could be increased to 0.5 g in the future.

5. FULL-SCALE DYNAMIC TESTS

A program of dynamic testing is currently underway. In these tests, the vehicle is fitted with an outrigger to prevent total rollover. It is fitted with trolleys to measure roll angles and accelerometers to measure lateral accelerations in the tractor and trailer.

The purpose of these dynamic tests is three-fold : (i) to verify the steady-state rollover limit obtained by static tilt testing and the computer model, (ii) to study dynamic effects inaccessible to the tilt test (liquid slosh, suspension backlash, etc.) and (iii) to study the driver's role in preventing rollover. For the former purpose, a circular course is being used. For the latter purposes, three manoeuvres - the double lane-change, J-turn and figure-of-eight - are being used.

6. WIDER APPLICATIONS OF THE RESEARCH

6.1 Size and Weight Regulations

(a) Stability of existing Australian vehicle combinations is disadvantaged by the relatively high axle group load permitted on tandems as compared to triaxles. For the same payload, a trailer/drive distribution of approximately 21/12 t is optimum and produces a 6.5 per cent improvement in wheel lift lateral acceleration.

(b) Increasing the total trailer sprung weight reduces stability to the extent of 0.005 g per tonne over the range 20 t to 30 t (this assumes that the centre-of-gravity height does not change).

(c) At 4.3 m (with stock crates carrying cattle in some States up to 4.6 m), Australian trucks are the highest in the OECD countries. This destabilising effect is offset by the width and Australia, in company with most countries, adopts a maximum width of 2.5 m. (Exceptions are Sweden (2.6 m) and US (2.44 m).) Widening vehicles from 2.5 m to 2.6 m would have the potential for an increase of 16 per cent in wheel lift lateral acceleration.

6.2 Trade-off with Road Damage

Previous research (3) was directed at identifying axle group suspension types generating severe dynamic road loading. Walking beam drive axle suspensions were found to be in this category. However, it was widely believed that stiff walking beam suspensions lent stability to high centre-of-gravity loads. This has been borne out by the current stability test program, but other drive axle suspensions of the four-spring variety provide better stability than the walking beam. While these were not tested for dynamic pavement loading, good results for the four-spring suspension in its trailer configuration (3) would indicate a reasonably favourable performance for the drive axle versions.

One of the very best suspensions in terms of dynamic pavement loading, the torsion bar suspension, leads to poor stability. However, a re-designed version possesses acceptable stability characteristics while retaining the same load-sharing and damping features as that tested for dynamic pavement loading.

The above key examples show that good stability and reduced dynamic pavement loading are not necessarily mutually exclusive characteristics of axle group suspensions. In general, drive axle suspensions have never been designed for either characteristic and there is considerable room for improvement in both areas. A proposed Australian Design Rule for suspensions to control dynamic road loading need not lead to a reduction in stability.

6.3 Wide Single Tyres

Wide tyres can lead to improved stability and industry experience has confirmed their productivity benefits in terms of reduced tare weight and fuel consumption. ARRB has recently carried out a field study of the pavement effects of 15, 16.5 and 18 inch tyres relative to conventional duals. This has been done for triaxle loads between 18 t and 24 t and tandem loads up to 18 t. Data is currently being analysed but indications are that the wide singles do have a greater road damage potential than dual tyres. Road regulating authorities therefore need to trade off the productivity benefits in road transport using wide singles against likely increased road costs.

6.4 Road Trains

Stock crates carrying cattle are a particular vehicle class prone to rollover. The computer model predicts rollover at 0.25 g, as compared to the range 0.35 to

0.45 g for articulated tankers. As current stock crate heights appear to be necessary to carry two decks of cattle, the only effective measures available are increased width (2.6 m), wide single tyres and the use of the best suspensions. To increase stability to that of the tankers, all of the above measures are needed.

7. CONCLUSIONS

(a) Truck stability is an important issue in the examination of size and weight limits. Although increased trailer weight reduces stability, a better distribution of the load between the prime mover and trailer axle groups will tend to offset this effect.

(b) Limitation of vehicle height and/or centre-of-gravity position is the most effective means of controlling stability. Increasing the width is almost as effective, but this is limited by other considerations. However, for the existing height and width situation, suspensions become the key influence and these can be selected according to the ARRB Users' Guide.

(c) Suspensions, especially tractor drive axle suspensions, need to be improved to provide more roll resistance. Fitment of wide single tyres in the place of conventional duals on trailers increases stability substantially, provided that wide axles are also fitted. However, there is a penalty in terms of road damage.

(d) Stable suspensions do not necessarily cause increased dynamic pavement loading.

8. REFERENCES

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(4) ERVIN, R.D., MALLIKARJUNARAO, C. and GILLESPIE, T.D. (1980). Future configuration of tank vehicles hauling flammable liquids in Michigan. Highway Safety Research Institute Report UM-HSRI-80-73-1.

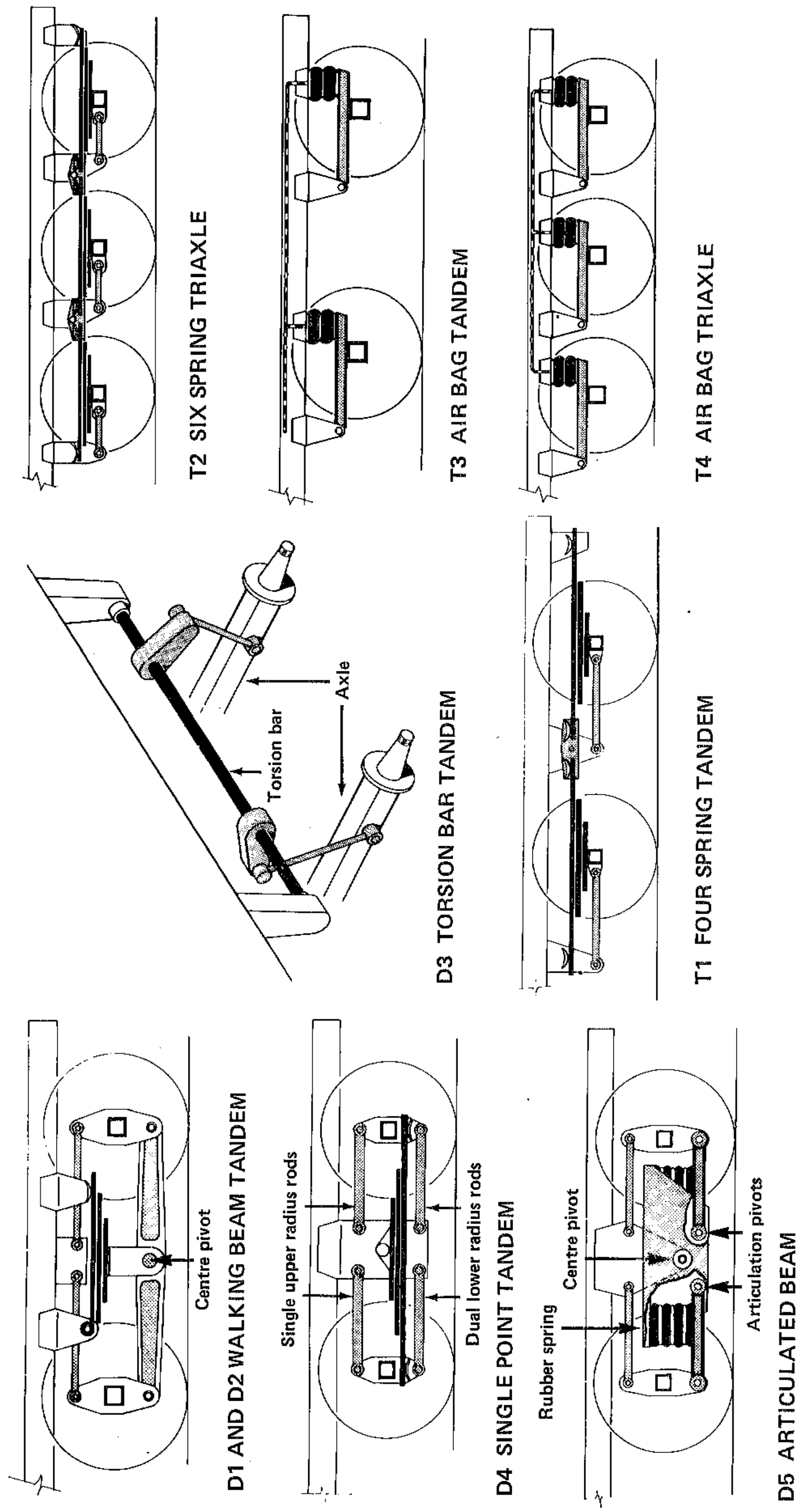


Fig.1. Illustration of suspension types used on Australian roads

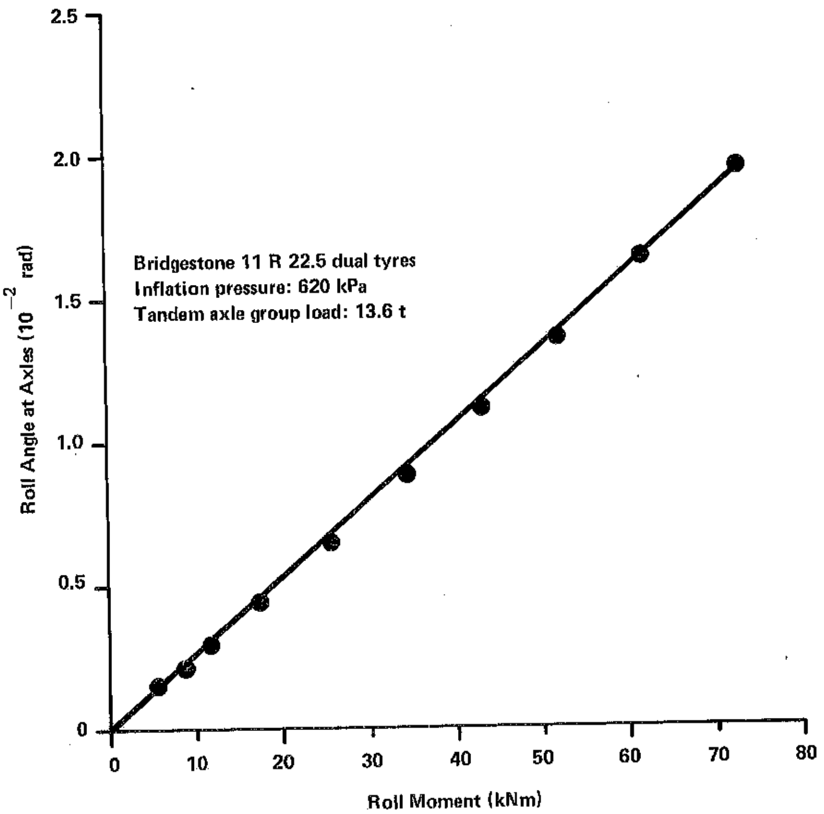


Fig.2. Typical tyre roll characteristic

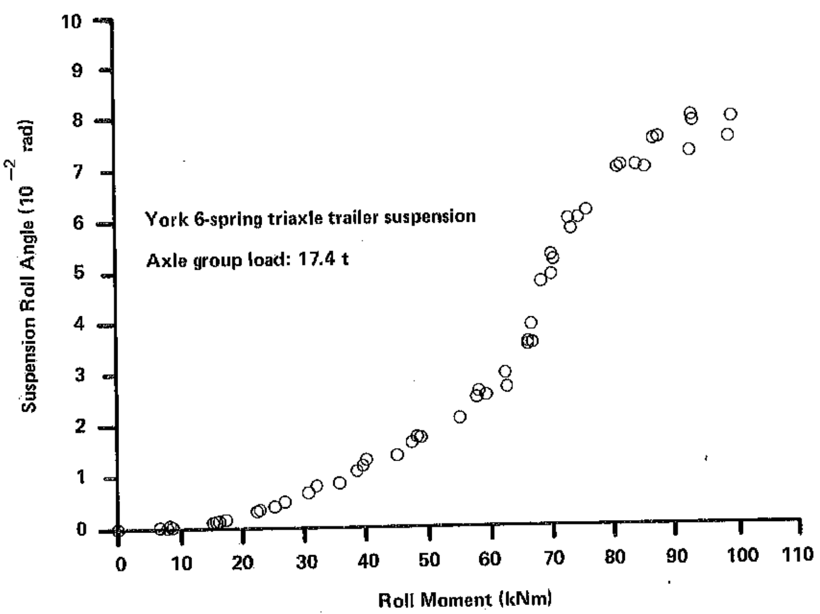
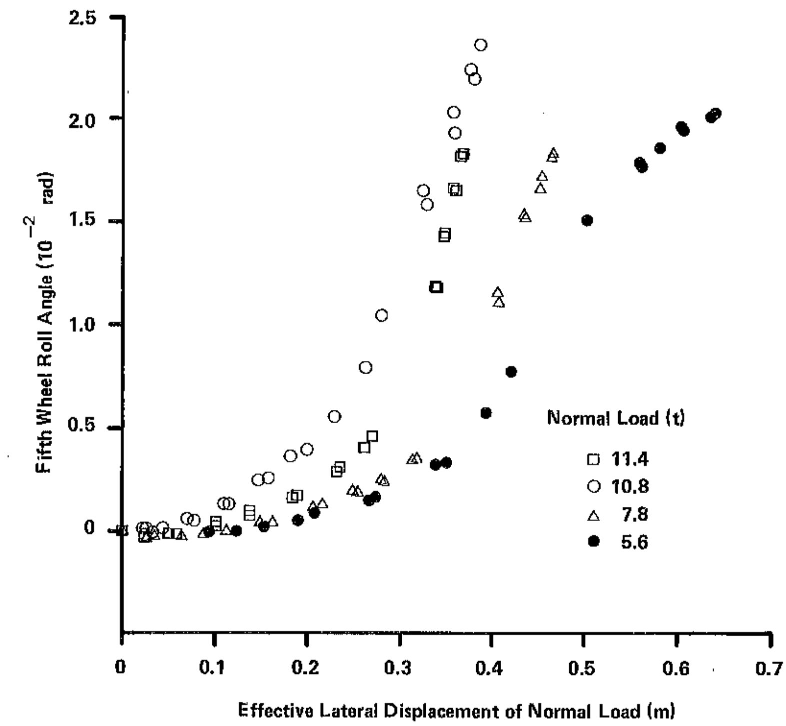
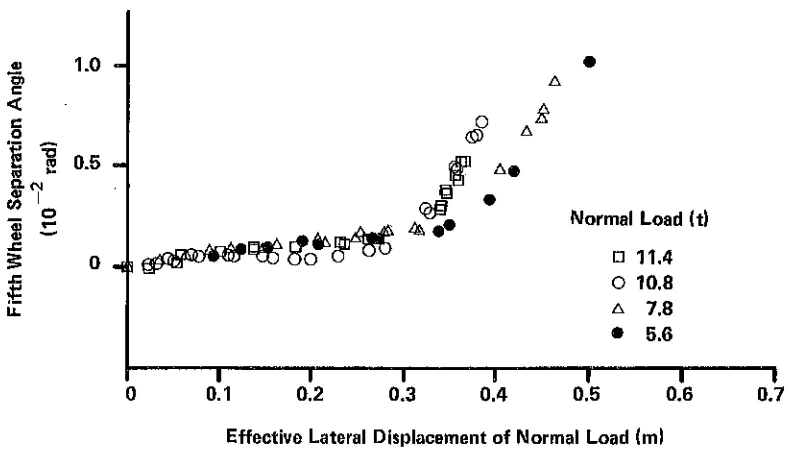


Fig.3. Example of suspension roll characteristic



(a) Structural compliance



(b) Separation

Fig.4. Typical fifth wheel coupling characteristics:

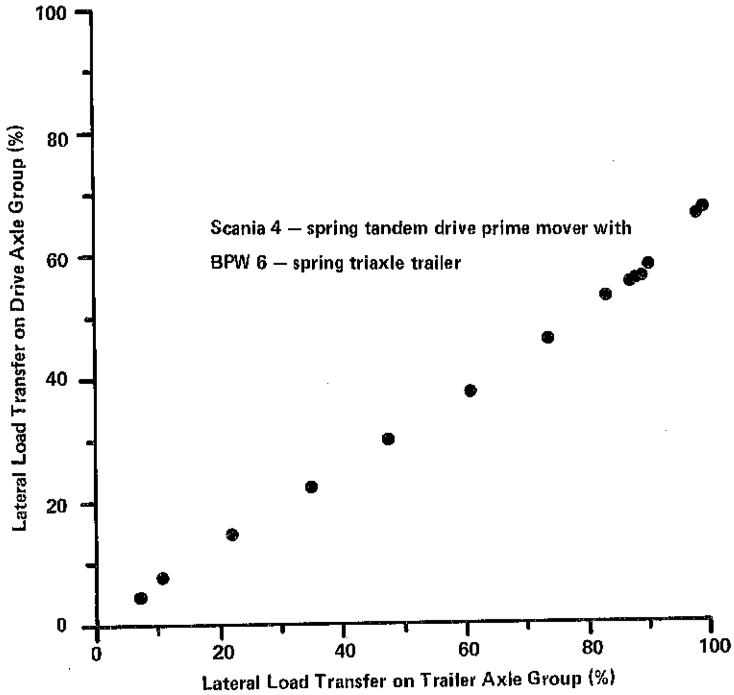


Fig.5. Typical plot of rollover process

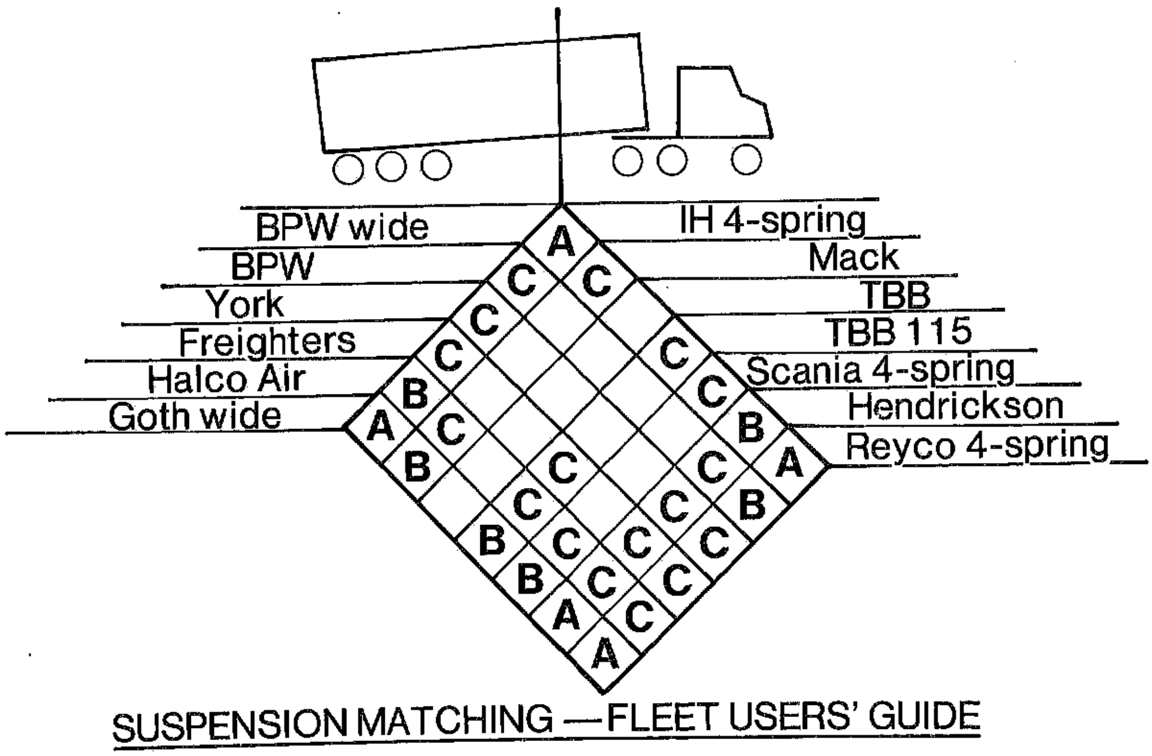


Fig.6. Guide to matching tractor and trailer suspensions