The influence of passenger payload on the stability of bodied three wheel vehicles

M Dodd
The influence of passenger payload on the stability of bodied three wheel vehicles

by M Dodd (TRL)

Prepared for: Project Record: S0808/V3
The influence of passenger payload on bodied three wheel vehicles
Client: Department for Transport, TTS Division
(Adrian Burrows)

Copyright Transport Research Laboratory September 2009

This Published Report has been prepared for Department for Transport. Published Project Reports are written primarily for the Client rather than for a general audience and are published with the Client’s approval.

The views expressed are those of the author(s) and not necessarily those of Department for Transport.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date Approved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Manager</td>
<td></td>
</tr>
<tr>
<td>James Nelson</td>
<td>08/04/2010</td>
</tr>
<tr>
<td>Technical Referee</td>
<td></td>
</tr>
<tr>
<td>Iain Knight</td>
<td>08/04/2010</td>
</tr>
</tbody>
</table>
When purchased in hard copy, this publication is printed on paper that is FSC (Forest Stewardship Council) registered and TCF (Totally Chlorine Free) registered.
Executive summary

A motorised tricycle entering service in the UK must be approved under either the European Whole Vehicle Type Approval (ECWVTA) or Motorcycle Single Vehicle Approval (MSVA) schemes. Approval is required before a vehicle can be registered for use on the road.

The ECWVTA and MSVA schemes require compliance to Council Directive 93/93/EEC (Masses and Dimensions). This includes a limit on the maximum 'passenger payload' for tricycles of 300kg and quadricycles of 200kg. Whilst the mass of the rider/driver is specified (75 kg), the mass of the passenger is not defined. It is understood that the intention of the directive was to limit the number of passengers that could be carried. However, there is evidence that in practice the passenger payload limits are not enforced at type approval.

The UK Department for Transport commissioned this project to investigate the potential impact to the safety and stability of certain bodied three wheel vehicles approved under the current schemes when they exceed recommended passenger payload limits by virtue of the number of approved seating positions.

An MMW built ‘Tuk-Tuk’ designed to carry a driver plus six passengers in sideways facing seats was used as a test vehicle in this project. The load carried by each wheel of the vehicle was measured to determine the transverse and longitudinal position of the centre of gravity. Static tilt tests were used to determine the height of the centre of gravity and to show how changing the loading of the vehicle affected this and the steady state roll stability of the vehicle.

The vehicle was subjected to tilt tests in four load conditions:

- Unladen (kerb-weight including driver);
- Part-Laden (300kg passenger payload evenly distributed to represent the maximum permitted passenger payload);
- Fully Laden (every seat loaded with 75kg);
- Offset laden (every seat on one side of the vehicle loaded with 75kg).

Two tilt tests were carried out for each of the four load conditions with the test vehicle, one where the vehicle was tilted towards its nearside and one where the vehicle was tilted towards its offside. In each case the tilt platform angle and the angle of the vehicle body at its front and rear were recorded at the instant that the first upslope wheel lifted from the platform.

The results showed that as the mass of the vehicle was increased the maximum tilt platform angle that could be achieved reduced; indicating that increasing the number of passengers carried by the vehicle raised the height of the centre of gravity and reduced its static stability.

Analysis of the tilt test results also showed that having a full passenger load of 450kg reduces the maximum cornering speed of the vehicle by 4% compared with the same vehicle with maximum permitted passenger load of 300kg (as defined in Directive 93/93/EC). On a 20m radius bend this 4% difference would equate to a speed differential of approximately 0.9mile/h (i.e. 22.3 mile/h for the part-laden condition and 21.4 mile/h for fully laden), for a 60m radius bend the difference would be approximately 1.6mile/h (i.e. 38.7 mile/h for the part-laden condition and 37.1mile/h for fully laden).

A comparison of the tilt test results to the roll stability requirements for other vehicle types showed that the performance of the Tuk Tuk fell somewhere between that of an HGV and a PSV and was less than a typical SUV. However, unlike the HGV and PSV, the driver/owner of a Tuk Tuk is not required to have any special training or license.
Abstract

The European Whole Vehicle Type Approval (ECWVTA) and Motorcycle Single Vehicle Approval (MSVA) schemes require compliance to Council Directive 93/93/EEC (Masses and Dimensions). This includes a limit on the maximum 'passenger payload' for tricycles of 300kg and quadricycles of 200kg. The mass of the passenger is not defined within the directive and because 6-seater vehicles are available on the market in the UK there is evidence that in practice the passenger payload limits are not enforced at type approval.

The UK Department for Transport commissioned this project to investigate the potential impact to the safety and stability of certain bodied three wheel vehicles approved under the current schemes when they exceed recommended passenger payload limits by virtue of the number of approved seating positions.

Analysis of the tilt test results showed that having a full passenger load of 450kg reduced the maximum cornering speed of the vehicle by 4% compared with the same vehicle with maximum permitted passenger load of 300kg (as defined in Directive 93/93/EC). A comparison of the tilt test results to the roll stability requirements for other vehicle types showed that the performance of the Tuk Tuk fell somewhere between that of an HGV and a PSV and was less than a typical SUV. However, unlike the HGV and PSV, the driver/owner of a Tuk Tuk is not required to have any special training or license.

1 Introduction

A motorised tricycle entering service in the UK must be approved under either the European Whole Vehicle Type Approval (ECWVTA) or Motorcycle Single Vehicle Approval (MSVA) schemes. Approval is required before a vehicle can be registered for use on the road.

ECWVTA is a process which ensures that vehicles meet the appropriate minimum level of safety and environmental performance. Testing is carried out (or witnessed) by an authorised Type Approval Authority based in any European Union Member State, to harmonised technical requirements given in various separate Directives and in accordance with formally agreed procedures.

MSVA is an alternative route to registration often used to approve amateur built vehicles, vehicles built from kits, some imported non-type approved vehicles and vehicles produced in very low volume. The scheme is run under the Motor Cycles Etc. (Single Vehicle Approval) Regulations 2003.

The ECWVTA and MSVA schemes require compliance to Council Directive 93/93/EEC (Masses and Dimensions). This includes a limit on the maximum 'passenger payload' for tricycles of 300kg and quadricycles of 200kg. Whilst the mass of the rider / driver is specified (75 kg), the mass of the passenger is not defined. It is understood that the intention of the directive was to limit the number of passengers that could be carried. However, because 6-seater vehicles are available on the market in the UK there is evidence that in practice the passenger payload limits are not enforced at type approval.

The UK Department for Transport commissioned this project to investigate the potential impact to the safety and stability of certain bodied three wheel vehicles approved under the current schemes when they exceed recommended passenger payload limits by virtue of the number of approved seating positions.

The load carried by each wheel of a six-seat vehicle was measured to determine the transverse and longitudinal position of the centre of gravity. The vehicle was also subject to a static tilt test to determine the height of the centre of gravity and to show how changing the loading of the vehicle affected this and the steady state roll stability of the vehicle.
2 Legislation

In Europe, the design and construction of road vehicles is controlled by the Type Approval regulations. Directive 70/156, as amended, defines the European Whole Vehicle Type Approval (ECWVTA) process for M1 vehicles (passenger cars) and the type approval process for other vehicles of category M, N and O (all passenger and goods vehicles).

Directive 2007/46/EC recasts this to incorporate amendments and extend the ECWVTA process to all M, N and O category vehicles. Directive 2002/24/EC defines the Type Approval Process for two and three wheeled motor vehicles of category L (which also includes requirements for four wheeled "quadricycles"). Each of these framework Directives refers to a wide range of separate Directives and/or UNECE Regulations, which define the relevant technical requirements for different vehicle types.

Single Vehicle Approval (SVA) represents an alternative route to registration often used to approve vehicles produced in very low volume, amateur built vehicles, vehicles built from kits and some imported vehicles that do not have European Type approval. For two and three wheeled motor vehicles this scheme is run under the Motorcycles Etc. (Single Vehicle Approval) Regulations 2003, known as MSVA.

Directive 2002/24/EC and MSVA both require compliance with Council Directive 93/93/EC (Masses and Dimensions). This imposes a limit on the maximum passenger payload of 300kg on tricycles and 200kg on quadricycles. However, none of the regulations directly specify a maximum number of passengers or define a mass considered to represent one passenger. In practice, the way that the regulations are interpreted by European approval authorities means that the number of seats on a tricycle or quadricycle is not controlled.

In recent years, some types of three wheeled vehicle including those known as “Tuk Tuks”, have been approved with as many as 6 passenger seats or with bench seats that do not have a defined number of seat positions and could potentially carry a greater number of passengers. One example was found in an internet search where a model with bench seats was advertised as carrying 6 to 10 passengers even though the more detailed specification listed a seating capacity of 7 and a GVW of 650kg. By convention, most regulations where passenger mass are relevant are based on an assumption that each passenger will have a mass of 75kg, comprising 68kg for the passenger themselves and 7kg for luggage. A tricycle approved with 6 passenger seats could potentially, therefore, carry a passenger payload of at least 450kg, 50% greater than Directive 93/93/EC specifies. If 10 such passengers were carried, the weight of the passengers alone (i.e. excluding the vehicle and driver) would exceed the stated GVW of the vehicle and more than double the maximum passenger payload permitted by Directive 93/93/EC.

---

1http://www.tuktuksforsale.co.uk/
3 Test vehicle

The test vehicle used in the study was an MMW built ‘Tuk-Tuk’ with a 650cc Daihatsu 3-cylinder engine. The vehicle has a maximum speed of 65mile/h and is designed to carry a driver plus six passengers in longitudinal benches, as shown in Figure 1. Further details of the vehicle are provided in Appendix A.

![Figure 1: MMW Tuk-Tuk test vehicle.](image)

3.1 Vehicle mass

The weight at each wheel of the vehicle was measured in each of the following four loading conditions:

1. ‘Driver only’ (kerb-weight including driver);
2. ‘Part-Laden’ (300kg passenger payload evenly distributed to represent the maximum permitted passenger payload);
3. ‘Fully Laden’ (every seat loaded with 75kg at a height representative of human passengers);
4. ‘Offset Laden’ (every seat on one side of the vehicle loaded with 75kg at a height representative of human passengers).

3.1.1 Driver only

In its ‘Driver only’ condition the mass of the vehicle was measured to be 880kg. This is different to the vehicle’s technical specification, supplied by the dealer, which stated that the unladen weight was 650kg. The reasons for this difference are unknown but it is possible that different conditions with respect to fuel and fluids could partially explain the difference.
### Table 1: Mass of ‘Driver only’ test vehicle.

<table>
<thead>
<tr>
<th>Wheel loads (kg)</th>
<th>Axle loads (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>Front</td>
<td>270</td>
</tr>
<tr>
<td>Left Rear</td>
<td>Rear</td>
<td>295</td>
</tr>
<tr>
<td>Right Rear</td>
<td></td>
<td>315</td>
</tr>
<tr>
<td></td>
<td></td>
<td>880</td>
</tr>
</tbody>
</table>

#### 3.1.2 Part laden (300kg passenger payload)

To achieve a passenger payload of 300kg the vehicle was loaded with four water dummies on the passenger seats and one water dummy on the driver seat, as shown in Figure 2. Each of these dummies weighed 75kg. This brought the overall mass of the vehicle to 1180kg.

![Figure 2: Layout of water dummies for part-laden test condition.](image)

Table 2 shows the loads recorded at each wheel. The technical specification provided by the vehicle dealer stated that the maximum axle-load for the rear axle was 900kg. By loading the vehicle with “passengers” in the rearmost four seats of the vehicle, Table 2 shows that it was possible to exceed the maximum permitted axle load even though the passenger payload was within the permitted limits.

This condition was used for the tilt test because it represented the worst case loading condition within the permitted passenger payload limits.
Table 2: Mass of part-laden test vehicle (300kg passenger payload).

<table>
<thead>
<tr>
<th>Wheel loads (kg)</th>
<th>Axle loads (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front 250</td>
<td>Front 250</td>
<td>1,180</td>
</tr>
<tr>
<td>Left Rear 450</td>
<td>Rear 930</td>
<td></td>
</tr>
<tr>
<td>Right Rear 480</td>
<td></td>
<td>3,180</td>
</tr>
</tbody>
</table>

3.1.3  **Fully laden (450kg passenger payload)**

For this test condition a water dummy weighing 75kg was placed on each of the six passenger seats and on the driver’s seat (Figure 3).

**Figure 3: Layout of water dummies for fully-laden test condition.**

The overall mass of the vehicle in this condition was 1,330kg. Although the axle loads in this condition were in excess of the maximum load specified by the manufacturer, the maximum load imposed on a single tyre (540kg) was well within the load rating for the tyre, which specifies they can carry up to 900kg each. Further details on the tyre load rating are provided in Appendix A.

Table 3: Mass of fully-laden test vehicle (450kg passenger payload).

<table>
<thead>
<tr>
<th>Wheel loads (kg)</th>
<th>Axle loads (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front 295</td>
<td>Front 295</td>
<td>1,330</td>
</tr>
<tr>
<td>Left Rear 495</td>
<td>Rear 1035</td>
<td></td>
</tr>
<tr>
<td>Right Rear 540</td>
<td></td>
<td>3,330</td>
</tr>
</tbody>
</table>
3.1.4 Offset laden
This configuration was designed to represent when all of the seats along one side of the vehicle are occupied and the seats on the other side are empty (Figure 4).

![Figure 4: Layout of water dummies for offset-laden test condition.](image)

The overall mass of the vehicle in this condition was 1,105kg.

**Table 4: Mass of offset-laden test vehicle.**

<table>
<thead>
<tr>
<th>Wheel loads (kg)</th>
<th>Axle loads (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>Front</td>
<td>280</td>
</tr>
<tr>
<td>Left Rear</td>
<td>Rear</td>
<td>310</td>
</tr>
<tr>
<td>Right Rear</td>
<td></td>
<td>515</td>
</tr>
</tbody>
</table>

The overall mass is 1,105kg.
4 Test procedure

The procedure for each tilt test involved parking the test vehicle on a tilting platform such that the rear wheel on the lower side and the front wheel were parallel to the axis of rotation of the tilt platform (Figure 5). The wheels on the lower side of the vehicle were then chocked to prevent sideways sliding and chains were attached to the chassis to prevent total rollover.

This is the same orientation that is defined in Directive 89/240/EEC which describes the method for testing the lateral stability of self-propelled industrial trucks (i.e. fork-lifts).

During a tilt test a three wheel vehicle is positioned at an angle because this is the worst case scenario for a rollover condition, i.e. if wheel lift occurs during normal driving, two wheels remain in contact with the ground whilst the third wheel lifts up.

The platform was then tilted at a slow and controlled rate until the first upslope wheel lost contact with the platform. At this point the platform angle, front body angle and rear body angle were recorded.

The platform was then lowered and the test vehicle removed so that it could be driven in a figure of eight to settle the suspension, before being driven onto the tilt platform again and tilted in the opposite direction.

The test facility used for the tests is owned and operated by QinetiQ. All procedures involving the operation of the tilt table were carried out by QinetiQ staff and witnessed by TRL staff.

Figure 5: Orientation of test vehicle during tilt tests.
5 Test results

Two tilt tests were carried out for each load condition, one where the vehicle was tilted towards its nearside and one where the vehicle was tilted towards its offside.

The average results of the tilt tests in each load condition are shown in Table 5. Photographs of the vehicle taken during the tilt table tests are shown in Appendix B and the individual test results are shown in Appendix C.

Table 5: Average tilt table readings for each load condition.

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Platform angle (deg)</th>
<th>Front body angle (deg)</th>
<th>Rear body angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver only</td>
<td>29.3</td>
<td>31.9</td>
<td>33.4</td>
</tr>
<tr>
<td>Part-laden</td>
<td>26.9</td>
<td>31.9</td>
<td>34.4</td>
</tr>
<tr>
<td>Fully-laden</td>
<td>25.0</td>
<td>29.0</td>
<td>29.7</td>
</tr>
<tr>
<td>Offset-laden</td>
<td>26.0</td>
<td>30.6</td>
<td>30.9</td>
</tr>
</tbody>
</table>

The results show that as the mass of the vehicle was increased the maximum tilt platform angle that could be achieved reduced. This indicates that increasing the number of passengers carried by the vehicle raises the height of the centre of gravity.

The overall mass of the offset laden condition was similar to the part-laden condition and the average platform and body angles recorded were also similar to the part laden condition.
6 Analysis

6.1 Calculation of centre of gravity

Using the wheel loads shown in section 3.1, and the results of the tilt tests it is possible to calculate the position of the centre of gravity of the test vehicle in the different load conditions.

The calculations used are shown in Appendix D to this report, and the results (based on the average of the two tilt tests for each load condition) are shown in Table 6 below.

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Longitudinal, X (m)*</th>
<th>Lateral, Y (m)**</th>
<th>Height, H (m)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver only</td>
<td>1.73</td>
<td>-0.01</td>
<td>0.72</td>
</tr>
<tr>
<td>Part-laden</td>
<td>1.97</td>
<td>-0.02</td>
<td>0.90</td>
</tr>
<tr>
<td>Fully-laden</td>
<td>1.95</td>
<td>-0.02</td>
<td>0.97</td>
</tr>
<tr>
<td>Offset-laden</td>
<td>1.87</td>
<td>-0.11</td>
<td>0.87</td>
</tr>
</tbody>
</table>

*: Behind the front wheel.
**: To the left of the centre line of the vehicle (when viewed from the rear)
***: Above the ground plane

The above results show that the additional weight of the passengers in the test vehicle moved the centre of gravity rearwards and the height of the centre of gravity was also increased.

Only having passengers on one side of the vehicle (offset-laden condition) had the effect of moving the centre of gravity of the vehicle further to the right.

6.2 Rollover threshold

When a vehicle negotiates a corner the friction between the tyres and the road creates a lateral "centripetal force". Newton's laws state that, for every action there must be an equal and opposite reaction. Therefore, there must be an equal and opposite force reacting against the frictional force. This reacting force is known as the "centrifugal force" and it acts outwards from the centre of the corner through the centre of gravity of the vehicle as shown in Figure 6.
Figure 6: Rear view of vehicle negotiating a right hand bend

Where,

- \( F \) = Frictional force (N)
- \( F_c \) = Centrifugal force (N)
- \( h \) = height of Centre of Gravity (C of G)
- \( M \) = Total mass of vehicle (kg).
- \( g \) = gravitational constant (= 9.81m/s²)
- \( T \) = Track width of vehicle (m)

Because the centrifugal force acts at a height in line with the vehicle’s centre of mass and the frictional force is acting at the tyre/road interface, the two forces act in combination to try to roll the vehicle over. This is counteracted by the weight of the vehicle acting vertically downwards, which acts to keep the vehicle on its wheels.

If the road is icy or slick, there is generally not a high enough "static frictional coefficient" to cause a rollover force and so generally the vehicle will start to slide instead.

Assuming there is sufficient grip for a rollover to occur, the tilt table angle can be used to approximate the lateral acceleration at which a vehicle would first start to rollover.

Previous research by TRL (Kemp et al, 1978) has shown that the tangent of the tilt table angle (\( \theta \)) at the point of wheel lift is mathematically equivalent to the static rollover threshold of a vehicle in units of g. This research also showed that results of tilt tests correlated well with full scale steady state rollover tests on a research track.
\[
\tan \theta = a
\]

Where,
\[
\begin{align*}
\theta &= \text{tilt table angle (degree)} \\
a &= \text{lateral acceleration of vehicle at rollover threshold (g)}
\end{align*}
\]

This is a simplified approach which ignores effects such as transient suspension movement and load shift, but it does provide a reasonable method to compare the relative performance of different vehicles or loading conditions.

Using the estimated values of lateral acceleration at the point of rollover, the following equation can be used to estimate the maximum speed a vehicle could achieve around a fixed radius bend:

\[
a = \frac{V^2}{R}
\]

Where:
\[
\begin{align*}
V &= \text{vehicle speed (m/s)} \\
R &= \text{radius of bend (m)}
\end{align*}
\]

As an example, the average tilt platform angle for the unladen test vehicle was 29.3°. Using this angle the lateral acceleration of the vehicle at the point of rollover can be estimated to be 0.56g. If it was assumed that the test vehicle was travelling round a bend on a surface with a high coefficient of friction and with a fixed radius of 20m, the estimated maximum speed that the vehicle could achieve is 23.4 mile/h.

Table 7 shows similar estimates for each load condition that was tested.

**Table 7: Estimated rollover threshold for different load conditions on a 20m radius bend.**

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Platform angle (deg)</th>
<th>Lateral acceleration (g)</th>
<th>Maximum speed (mile/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver only</td>
<td>29.3</td>
<td>0.56</td>
<td>23.4</td>
</tr>
<tr>
<td>Part-laden</td>
<td>26.9</td>
<td>0.51</td>
<td>22.3</td>
</tr>
<tr>
<td>Fully-laden</td>
<td>25.0</td>
<td>0.47</td>
<td>21.4</td>
</tr>
<tr>
<td>Offset-laden (left)</td>
<td>31.3</td>
<td>0.61</td>
<td>24.4</td>
</tr>
<tr>
<td>Offset-laden (right)</td>
<td>20.7</td>
<td>0.38</td>
<td>19.3</td>
</tr>
</tbody>
</table>

As the mass of the vehicle was increased the maximum tilt platform angle that could be achieved reduced. This in turn means that the maximum lateral acceleration that the vehicle can achieve before rollover also reduces. This is illustrated in Figure 7 which shows how maximum corner speed varies for different corner radii in the different load conditions.
Figure 7: Relationship between corner radius and vehicle speed for different loading conditions.

Figure 7 shows that the difference between the maximum cornering speed for the part-laden condition is 5% lower than the unladen condition. Similarly the maximum corner speed for the fully-laden condition is 9% lower than the 'Driver-only' condition.

This indicates that having a full passenger load of 450kg reduces the maximum cornering speed of the vehicle by 4% compared with the same vehicle with maximum permitted passenger load of 300kg (as defined in Directive 93/93/EC). On a 20m radius bend this 4% difference would equate to a speed differential of approximately 0.9 mile/h (i.e. 22.3 mile/h for the part-laden condition and 21.4 mile/h for fully laden), for a 60m radius bend the difference would be approximately 1.6 mile/h (i.e. 38.7 mile/h for the part-laden condition and 37.1 mile/h for fully laden).

For the offset-laden condition, the passenger load was added to the right hand side of the vehicle. Figure 8 shows that this had the effect of moving the position of the centre of gravity towards the right side of the vehicle. Therefore when the vehicle was tilted to the left (representing a right hand bend) the effective track width of the vehicle increased which, in turn, meant the vehicle could achieve a higher tilt angle. Conversely, when the vehicle was tilted to the right (representing a left hand bend) the effective track of the vehicle was reduced and so a lower tilt angle was achieved.
Figure 8: Relationship between corner radius and vehicle speed for different loading conditions, including offset load conditions

6.3 Comparison to other vehicle types

The track width of the test vehicle (1.2m) is narrower than other types of vehicle such as a passenger car (which typically has a track width of around 1.7m) and an HGV (2.0m).

If the location of the centre of gravity of the test vehicle was kept constant then increasing the track width of the rear axle could help to improve the rollover performance because the lateral stability would be increased.

For example, Figure 9 shows the relationship between corner radius and maximum vehicle speed for the test vehicle in its fully laden condition. It illustrates that if the track width of the test vehicle was increased to 1.7m or 2.0m, then the rollover threshold could be increased by 39% and 60% respectively.
For most HGVs there is no required standard of roll stability although previous research has indicated that many HGVs have a rollover threshold of 0.3g to 0.4g when fully laden (Winkler, 2000) and that occasionally some trucks could have a threshold as low as 0.2g (Brock et al, 1978; Ervin & Nisonger, 1982; Sweatman, 1993).

Ervin (1983) studied accident data to show the influence of HGV stability on the likelihood of involvement in a rollover accident and the results are reproduced in Figure 10, below. The results from the tilt tests with the ‘Driver-only’, part-laden and fully-laden Tuk Tuk have been overlaid on the graph. This shows that, based on the research by Ervin, the difference in rollover threshold for the part laden and the fully laden conditions translates to an increase in accident risk of approximately 4%.

Tilt tests are a recognised method to assess the roll stability of a vehicle. Although the fundamental geometry and load distribution are the dominant effects in roll stability, dynamic effects can substantially change the thresholds at which rollover will occur in practice.

For example, the action of braking causes dynamic load transfer which moves the centre of gravity forwards. This in turn reduces the effective track width of the vehicles and, if braking occurs on a bend, can further increase the likelihood of rollover.

The tilt test results showed that as the mass of the vehicle increased, when more passengers were added to the vehicle, the height of the centre of gravity was raised and the longitudinal position of the centre of gravity became more biased to the rear. In very general terms an increase in mass means an increase in momentum and, if the rear of the vehicle has a greater momentum than the front, this can lead to a greater risk of oversteer as a result of braking or lifting off mid corner. However, it is important to recognise that the dynamic performance of a vehicle can also be influenced by other factors such as suspension type and setup, tyre type, wear and pressures as well as the driving style of the driver.
UNECE Regulation 111 came into force on December 28th 2000 and introduces a minimum rollover threshold of 0.41g. This regulation is only applicable to tank vehicles, which represent a particular high risk if they become involved in rollover accidents because of the possibility of hazardous chemical leaks and fires. Conformance with the requirements can be demonstrated using a standardised calculation supplied as part of the regulation but if the value predicted is close to the limit the calculation must be verified by a tilt table test. In this case the vehicle would need to achieve a tilt angle of at least 23 degrees in both directions.

Directive 2001/85/EC specifies a stability test for passenger vehicles of category M2 and M3. The test specifies that the vehicle must be at its running order mass. The minimum requirement for approval is that the vehicle would need to achieve a tilt table angle of at least 28 degrees. Prior to this directive, the requirements in the UK were applied by a tilt test in the Certificate of Initial Fitness, Equipment and Use (CoIF) certification. Previously single deck PSVs were tilted to 35 degrees and double deck PSVs to 28 degrees. The CoIF requirement was amended in line with Directive 2001/85/EC.

In America a rollover rating scheme has been developed for SUVs and vans. Typically passenger cars have a rollover threshold of 1.3g – 1.5g. SUVs, pick-up trucks and vans usually have values in the range of 1.0g - 1.3g. The rating scheme is based on the calculation of a static stability factor (SSF) and a dynamic avoidance manoeuvre known as the “fish-hook test”. These tests are used to determine the risk of a vehicle rolling over in a single vehicle accident. Figure 11 shows that the overall rating is dominated by the SSF. Since the scheme is designed for vehicles with a relatively high rollover threshold then lowest rollover threshold considered in Figure 11 is 0.95g, which is considerably higher than the result of the tilt tests in this project.

Figure 10: Relationship between static stability and likelihood of involvement in a rollover accident (Ervin, 1983).
A comparison of the tilt test results for the Tuk Tuk and the literature highlighted above shows that the Tuk Tuk had greater roll stability than a typical laden HGV. However, when laden, it would be too unstable to be approved as a bus and has less than half the stability of a typical SUV.

This indicates that the roll stability of the Tuk Tuk fell somewhere between that of an HGV and a PSV and was less than a typical SUV. However, unlike the HGV and PSV, the driver/owner of a Tuk Tuk is not required to have any special training or license.
7 Conclusions

1. An MMW built ‘Tuk-Tuk’ designed to carry a driver plus six passengers in sideways facing seats was used as a test vehicle in this project. The vehicle was subjected to tilt tests in four load conditions:
   - ‘Driver only’ (kerb-weight plus driver);
   - Part-Laden (300kg passenger payload evenly distributed to represent the maximum permitted passenger payload);
   - Fully Laden (every seat loaded with 75kg);
   - Offset laden (every seat on one side of the vehicle loaded with 75kg).

2. Two tilt tests were carried out for each of the four load conditions with the test vehicle, one where the vehicle was tilted towards its nearside and one where the vehicle was tilted towards its offside. In each case the tilt platform angle and the angle of the vehicle body at its front and rear were recorded at the instant that the first upslope wheel lifted from the platform.

3. The results showed that as the mass of the vehicle was increased the maximum tilt platform angle that could be achieved reduced; indicating that increasing the number of passengers carried by the vehicle raises the height of the centre of gravity and reducing its cornering performance.

4. Analysis of the tilt test results also showed that having a full passenger load of 450kg reduces the maximum cornering speed of the vehicle by 4% compared with the same vehicle with maximum permitted passenger load of 300kg (as defined in Directive 93/93/EC). On a 20m radius bend this 4% difference would equate to a speed differential of approximately 0.9mile/h, for a 60m radius bend the difference would be approximately 1.6mile/h.

5. A comparison of the tilt test results to the roll stability requirements for other vehicle types showed that the performance of the Tuk Tuk fell somewhere between that of an HGV and a PSV and was less than a typical SUV. However, unlike the HGV and PSV, the driver/owner of a Tuk Tuk is not required to have any special training or license.
Acknowledgements

The work described in this report was carried out in the Safety Division of the Transport Research Laboratory. The authors are grateful to Iain Knight who carried out the technical review and auditing of this report.

References


Winkler C (2000). Rollover of heavy commercial vehicles. UMTRI research review ISSN 0739 7100.
Appendix A  Vehicle specification

The test vehicle used in the study was an MMW built ‘Tuk-Tuk’. The vehicle was designed to carry a driver plus six passengers in longitudinal benches.

The mass and dimensions of the vehicle are:

- Unladen mass: 680kg
- Maximum payload: 685kg
- Overall length: 3.0m
- Overall Width: 1.25m
- Front Axle – Maximum Gross: 450kg
- Rear Axle – Maximum Gross: 900kg
- Top Speed: 65 mile/h

The vehicle was fitted with a 650cc Daihatsu 3-cylinder EF Series engine.

The vehicle was fitted with COMPASS ST5000 (155/70R12C 104/102N FRT) tyres on all wheels. Below is a guide to the tyre wall markings:

155 - Tyre width in mm
70 - Profile of the tyre (i.e. the height of the tyre is 70% of its width)
R - Radial construction
12 - Wheel rim diameter in inches
C - Type
104/102 - Load index. (Numerical code which gives the maximum load the tyre can carry). 104 = 900kg, 102 = 850kg
N - Speed rating (maximum permitted speed for use with tyre). N = 140km/h (87mile/h)
FRT - Service type identification. (FRT = Free rolling tyre)
Appendix B  Photograph of tilt tests

B.1 Unladen

B.2 Part-laden
B.3 Fully-laden

B.4 Offset-laden
## Appendix C  Tilt test results

### C.1 Unladen

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Tilt direction</th>
<th>Platform angle (deg)</th>
<th>Front body angle (deg)</th>
<th>Rear body angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nearside</td>
<td>30.5</td>
<td>32.9</td>
<td>34.6</td>
</tr>
<tr>
<td>2</td>
<td>Offside</td>
<td>28.0</td>
<td>30.8</td>
<td>32.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>29.3</strong></td>
<td><strong>31.9</strong></td>
<td><strong>33.4</strong></td>
</tr>
</tbody>
</table>

### C.2 Part-laden

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Tilt direction</th>
<th>Platform angle (deg)</th>
<th>Front body angle (deg)</th>
<th>Rear body angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nearside</td>
<td>27.6</td>
<td>32.0</td>
<td>36.5</td>
</tr>
<tr>
<td>2</td>
<td>Offside</td>
<td>26.2</td>
<td>31.8</td>
<td>32.3</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>26.9</strong></td>
<td><strong>31.9</strong></td>
<td><strong>34.4</strong></td>
</tr>
</tbody>
</table>

### C.3 Fully laden

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Tilt direction</th>
<th>Platform angle (deg)</th>
<th>Front body angle (deg)</th>
<th>Rear body angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nearside</td>
<td>25.3</td>
<td>30.3</td>
<td>31.2</td>
</tr>
<tr>
<td>2</td>
<td>Offside</td>
<td>24.6</td>
<td>27.7</td>
<td>28.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>25.0</strong></td>
<td><strong>29.0</strong></td>
<td><strong>29.7</strong></td>
</tr>
</tbody>
</table>

### C.4 Offset laden

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Tilt direction</th>
<th>Platform angle (deg)</th>
<th>Front body angle (deg)</th>
<th>Rear body angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nearside</td>
<td>20.7</td>
<td>23.9</td>
<td>24.3</td>
</tr>
<tr>
<td>2</td>
<td>Offside</td>
<td>31.3</td>
<td>36.3</td>
<td>36.8</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>26.0</strong></td>
<td><strong>30.6</strong></td>
<td><strong>30.9</strong></td>
</tr>
</tbody>
</table>
Appendix D  Determination of centre of gravity

D.1 Longitudinal position of centre of gravity

\[ X = \frac{M_R \times WB}{M} \quad \text{where} \quad M_R = M_{\text{RR}} + M_{\text{RL}} \]

X  = Longitudinal distance between the front wheel and the centre of gravity (m);
M_R  = Mass on rear axle (kg);
M_{\text{RR}}  = Mass on right rear wheel (kg);
M_{\text{RL}}  = Mass on left rear wheel (kg);
WB  = Wheelbase of vehicle (m);
M  = Total mass of vehicle (kg).

D.2 Lateral position of centre of gravity

\[ Y = X \times \frac{Y_R}{WB} \quad \text{where} \quad Y_R = \frac{T}{2} - \frac{M_{\text{RR}} \times T}{M_R} \]

Y  = Lateral position from centre of gravity (m);
X  = Longitudinal position (m)
Y_R  = Distance from the centre of gravity to the rear wheel (m);
T  = Distance from front to rear wheel (m);
WB  = Wheelbase (m);
M  = Total mass of vehicle (kg);
M_R  = Mass on rear axle (kg);
M_{\text{RR}}  = Mass on right rear wheel (kg);
M_{\text{RL}}  = Mass on left rear wheel (kg).
Where,

$Y$ = Position of centre of gravity to the left of the centre line of the vehicle (when viewed from the rear) (m);

$Y_R$ = Lateral distance to the left of the centre line of the vehicle (when viewed from the rear) (m);

$T$ = Track width of vehicle (m);
D.3 Height of centre of gravity

At the point when the final up slope wheel loses contact with the tilt table platform, the vehicle is at a balance point and, at this point, the centre of gravity of the vehicle will be positioned directly above the point about which the vehicle is rotating.

Since the vehicle was tilted at an angle to its longitudinal axis, and to account for any lateral offset in the position of the centre of gravity, two different equations are needed; one for when the vehicle is tilted to the left, and one for when it is tilted to the right.

\[
\begin{align*}
    h_L &= \frac{Z_L}{\tan \theta} \\
    h_R &= \frac{Z_R}{\tan \theta} \\
    Z_L &= ET_L \times \cos \alpha \\
    Z_R &= ET_R \times \cos \alpha
\end{align*}
\]

Where,

\[
\begin{align*}
    ET_L &= \frac{ET}{2} - Y \\
    ET_R &= \frac{ET}{2} + Y \\
    ET &= \frac{X \times T}{WB} \\
    \alpha &= \tan^{-1} \left( \frac{T}{2 \times WB} \right)
\end{align*}
\]

- \( h_L \) = Height of centre of gravity when tilted to the left (m);
- \( h_R \) = Height of centre of gravity when tilted to the right (m);
- \( Z_L \) = Perpendicular distance between centre of gravity and lower edge of vehicle, when tilted to the left (m);
- \( Z_R \) = Perpendicular distance between centre of gravity and lower edge of vehicle, when tilted to the right (m);
- \( ET \) = Effective track width of vehicle at longitudinal position of centre of gravity (m);
- \( ET_L \) = Lateral distance between centre of gravity and lower edge of vehicle, when tilted to the left (m);
- \( ET_R \) = Lateral distance between centre of gravity and lower edge of vehicle, when tilted to the right (m);
- \( Y \) = Position of centre of gravity to the left of the centre line of the vehicle (when viewed from the rear) (m);
- \( T \) = Track width of vehicle (measured from the centre of the rear tyres) (m);
- \( WB \) = Wheelbase of vehicle (m);
- \( M \) = Total mass of vehicle (kg);
- \( \theta \) = Tilt table angle (degree)
The influence of passenger payload on the stability of bodied three wheel vehicles

The European Whole Vehicle Type Approval (ECWVTA) and Motorcycle Single Vehicle Approval (MSVA) schemes require compliance to Council Directive 93/93/EEC (Masses and Dimensions). This includes a limit on the maximum ‘passenger payload’ for tricycles of 300kg and quadricycles of 200kg. The mass of the passenger is not defined within the directive and because 6-seater vehicles are available on the market in the UK there is evidence that in practice the passenger payload limits are not enforced at type approval.

The UK Department for Transport commissioned this project to investigate the potential impact to the safety and stability of certain bodied three wheel vehicles approved under the current schemes when they exceed recommended passenger payload limits by virtue of the number of approved seating positions.

Analysis of the tilt test results showed that having a full passenger load of 450kg reduced the maximum cornering speed of the vehicle by 4% compared with the same vehicle with maximum permitted passenger load of 300kg (as defined in Directive 93/93/EC). A comparison of the tilt test results to the roll stability requirements for other vehicle types showed that the performance of the Tuk Tuk fell somewhere between that of an HGV and a PSV and was less than a typical SUV. However, unlike the HGV and PSV, the driver/owner of a Tuk Tuk is not required to have any special training or license.

Other titles from this subject area


PPR291 Assessment of the Q dummy in the EC CHILD project. C Visvikis, M Le Claire, S Adams, J Carroll et al. 2007

PPR293 An assessment of the durability and reliability of typical hydraulically operated parking brakes fitted to quadricycles. C J Grover. 2007