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Tilting vehicles as an alternative for personal transport

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ABSTRACT

Nowadays, traffic is still largely based on conventional vehicles such as bicycles, motorcycles, passenger cars, trucks. Each of these vehicles has its advantages and disadvantages with respect to traveling conditions in terms of comfort (exposure against adverse weather conditions, effort vs. fun to drive,...), safety, energy-use (passenger to fuel ratio), restrictions related to infrastructure design and law enforced by authorities, etc.
In order to overcome the disadvantages, various attempts have been made to look for intermediate designs, combining the benefits of the different kind of conventional vehicles. Many of these ‘solutions’ are explored within the field of tilting vehicles (e.g. bicycles, motorcycles) as an alternative for personal transport, since they are expected to be efficient in use to move from one place to another (especially in urban areas) as well as to be less sensitive to traffic congestion.

The major advantage of a motorcycle with respect to a passenger car is the possibility of the driver to tilt during cornering and thereby maintaining stability whereas a passenger car will suffer from the risk of capsizing at high speed. For that reason, several initiatives were taken to design new types of narrow vehicles that offer the comfort of a passenger car, however with a tilting functionality that allows down-scaling in order to improve fuel economy as well as the efficiency in use in nowadays traffic conditions.
Such new solutions range from upgraded motorized bicycles up to very sophisticated tilting three-wheelers.

The presentation will discuss the use of tilting vehicles against the use of other vehicles in relationship to the individual mobility-requirements. It will then focus on the trends mentioned above (the new ‘solutions’ based on tilting vehicles) and discuss the performance characteristics (safety and manoeuvrability, environmental issues) in relationship to their design parameters.

NOWADAYS TRAFFIC, THREATS AND OPPORTUNITIES

What drives us to move? Considering figure 1 which applies to The Netherlands, one observes two major motives, to travel between home and work (to commute) and to visit friends and relatives, each in the order of 8 to 10 km/day. This suggests the bicycle to be a very competitive means of transport. In recent years, the distance between home and work seems to be increasing, as well as the elapsed distance we travel for recreational purposes.
Human drives mobility in economic sense, and it is therefore worthwhile to list his mobility requirements. A traveller selects his transportmode on the basis of a number of criteria [2]:

- ☐ **Traveltime should be as short as possible**, with **minimum delay** and therefore minimum changes between subsequent transportmodes.
- ☐ The estimated trip time should be **reliable**, with no unexpected delays in multimodal transfers or congestion and thus with reliable arrival and departure times in the transport chain at hand. It requires sufficient up to date and available information matching the need to plan a trip, accessibility etc.
- ☐ The trip should be **comfortable**, which again has to do with sufficient

information but also with personal safety, minimum mental stress, privacy, service and availability of food and drink, working conditions, parking possibilities, entertainment, etc.

- **Value for money**, meaning that costs are affordable and related to service paid for.
- Finally, there must be **independency and flexibility** of choice meaning that a traveller is able to select his way of transport at the time and place he desires, with good connections between different transport modes.

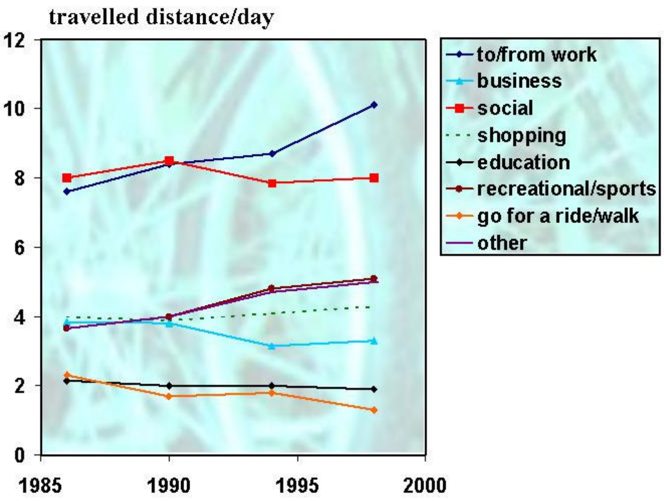

Figure 1.:Motives to move

And the traveller has a choice. In The Netherlands, the dominant means of transport is by car with 75 % of all travelled kilometres. In the last twenty years, car ownership has increased in Europe, Japan, as well as in the USA with a growing share of the car in the travelled kilometres, in spite of the large amounts of financial support that is given to public transport. In the Netherlands, the fixed annual investments from 1986 to 1997 for both construction and utilization of roads and for extending and improving regional public transport and the Dutch railway infrastructure have increased significantly. Whereas the investments in road infrastructure increased from 0.3 to 0.7 billion Euro, the investments for regional public transport infrastructure and railway infrastructure increased from 0.14 to more then 1 billion Euro. Per traveller kilometre, the public transport infrastructure appears to be a factor 10 more expensive than the road infrastructure, with less than 10 % of all traveller kilometres actually carried out by public transport! One should add to this the marginal societal costs (related to inefficiency of our traffic system, lack of safety, environmental damage etc.) and additional government funding related to the distance travelled. About 20 % of these costs can be linked to public transport, and most of them by no means covered by sufficiently charging the user.

In the USA, the support of public transport has only resulted in an increase in the bus and train fares in contrast to a reduction in costs to owe and run a car with 20 % in the same period. In The Netherlands, public transport cannot compete by far with private transport, as is illustrated in figure 2. For very small distances, travel time by car is about 20 to 30 % of the travel time by public transport. As a consequence, the share of public transport in all trips is very low, less than 6 %. With increasing distance (and a decreasing number

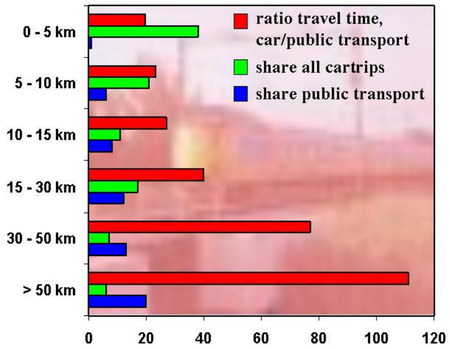

Figure 2.: Car versus public transport in The Netherlands

of cartrips), public transport and car become more competitive with about the same traveltime for distances beyond 50 km. One observes an increase of the share of public transport in this case up to 20 %

We conclude that there is still a large potential for private transport in spite of the increasing inefficiency on the road network as many people experience every day. Public transport doesn't seem to be the answer. Can the motorcycle help us here?

Motorcycles are smaller in size and do not carry so much unnecessary unused space and mass compared to passenger cars. In addition, they are manoeuvrable and have the possibility to pass and avoid the congested areas, reducing travel time. Because of the size and manoeuvrability, accessibility of locations such as in town-centres is not really a problem and motorcycles can be easily parked. This means that most of the criteria as used by a traveller to select his mode of transport are fulfilled. One would therefore expect a growth in the use of motorcycle in the preceding years.

In spite of the fact that the travelled kilometres by motorcycle amount still less than 1 % of all travelled kilometres, this amount has grown in The Netherlands with a factor 2.5 from 1985 until 1998. In the same time, the use of the car has grown with only 40 % in absolute sense, with the relative share in travelled kilometre not significantly changed, see figure 3 The percentage in number of trips, still very low, has almost doubled in size for the motorcycle, with no significant increase for the car within the same period. The number of motorcycles in The Netherlands has tripled over the last ten years, to be compared to a growth of about 2 % per years for passenger cars.

Let us consider the major motives to travel, as indicated in figure 1, in more detail. In travelling for social reasons one observes no significant change in the share (in traveller kilometres) in motorcycle-use. For commuting however, the share of motorcycle use has grown from 0.42 % in 1985 to over 1 % in 1998. Not a large contribution in absolute sense but definitely a clear trend. Motorcycles do not only serve as a means of transport to tour and have fun. People are apparently looking for ways to avoid traffic congestion and the motorcycle could be a good alternative. And this trend is still apparent, as is illustrated from the increase with 30 % of requests in the Netherlands to be examined for a motorcycle driving license from 2000 to 2001.

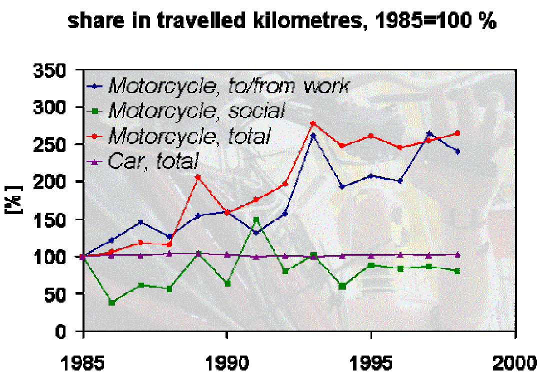

Figure 3.: Use of car vs. motorcycle

About two-third of all traveller kilometres by car are consumed by the driver. That means that in average about a mass of 800 kg is moved for each person using a car either as a driver or as a passenger. Consequently, a car-driver is usually transporting a lot of air and steel, which is not very efficient (especially considering the available space in our road network, parking potential etc.) but also contributing to our environmental problems such as the greenhouse effect (CO_2) .

For motorcycles, the transported mass is much lower resulting in a more efficient traveller kilometre to mass ratio and therefore a potential reduction in fuel consumption and emission. Indeed, fuel consumptions of 3 to 5 litre per 100 kilometres are not uncommon for a motorcycle, to be compared to 7 to 9 litre per 100 kilometres for passenger cars.

So, why not use the motorcycle more if there is so much to gain in terms of societal costs related to fuel consumption and efficiency?

One of the answers is the vulnerability of the motorcycle user, as can be concluded from the relative large number of casualties among

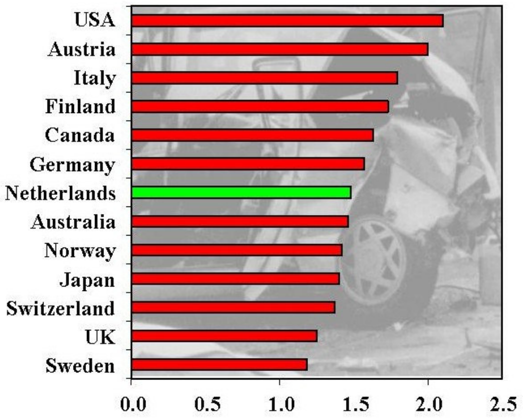

Figure 4.: Fatalities per 10000 vehicles (OECD 1998)

them. In 2001, 993 people were killed in traffic in The Netherlands (being one of the safest countries worldwide with 1.4 fatalities per 10000 vehicles, see figure 4), 76 of them were using a motorcycle or scooter. This means that, using a motorcycle, involves a fatality-risk that is 16 times that for travelling by car, which is unacceptable.

Some causes for this increased risk can be identified as follows:

- ☐ There is an increased exposure to damages and injuries during crashes. So, guard the rider! To illustrate this, we note that about 75 % of accidents with motorcycles are caused by the crash-partner.
- ☐ This is basically a matter of compatibility between different types of vehicle within the road-system, but with different aggressiveness.
- ☐ There is a strong interaction between the rider and the motorcycle. In that respect, a motorcycle is quite a different vehicle than the car. This results in extra complications in applying modern active safety measures, such as developed for passenger cars.
- ☐ In that respect, the motorcycle doesn't seem to be an issue in Intelligent Transport development programs. For example, we do not refer to Automated Motorcycle Guidance in the same way as we discuss Automated Vehicle Guidance. We mention here the research on a rider robot, carried out in Delft in the past (see figure 5) and recently taken up again.

Figure 5.: The historic rider-robot

Summarizing, a motorcycle is efficient in terms of fuel consumption, use of the road network, time delays due to congestion, parking requirements. On the other hand, the traffic safety for a motorcycle is still insufficient, compared to the use of a passenger car.

THE GAP BETWEEN THE CAR AND THE MOTORCYCLE.

The above considerations have motivated recently various manufacturers to develop new concepts of narrow vehicles that are able to tilt like a motorcycle but offer the comfort of a passenger car, allowing further downsizing of vehicles, enabling higher fuel efficiency. As a result, there seems to arise a whole new class of vehicles, which cannot be compared, to either passenger cars or motorcycles, with typical examples such as the Ford Gyron and the GM Lean Machine. More recent examples are the Daimler Benz Life Jet and the Carver of Brink Dynamics, see figures 6 and 7.

Figure 6.: Mercedez-Benz Life Jet, see [1]

Figure 7.: The Carver, see [3]

This paper discusses some results from a mathematical treatment of the dynamic behaviour of such vehicles, denoted here as a Narrow Tilting Vehicle (NTV).

These designs, two recent examples of which are shown in the figures 6 and 7, mean:

- ☐ smaller dimensions, hence more efficient transport.
- ☐ more opportunities for crash-protection, passive safety measures, to be incorporated in the car-type cover of the motorcycle-base
- ☐ in the same way more potential to fit this type of car in going-on developments on active chassis control, ITS measures, driver support, with the benefit of a safer and more comfortable vehicle.

From a marketing point of view, the question remains whether these design really appeal to the emotions of the motorcycle-rider.

A Narrow Tilting Vehicle may be described as a vehicle with at least three wheels and with part of the vehicle, usually the cockpit housing the driver and the possible passenger, actively tilting inside a bend during cornering. That means that the driver steering action is transferred in some way to a tilting torque moving the cockpit and bringing it to a steady state situation just like a motorcycle. One may distinguish basically three types of NTV's, identified as Tilting Three Wheeler in [10]:

- ☐ 1 front wheel, with all wheels tilting
- ☐ 2 front wheels, with all three tilting (e.g. Mercedes Benz Life Jet)
- ☐ 1 front wheel with only one wheel tilting (e.g. Carver)

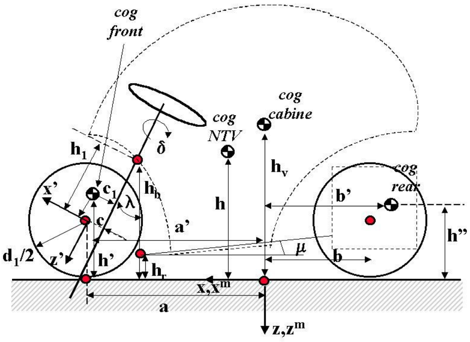

figure 8.: Model layout

The discussion will be based on the last type, see [5] and [6], being a vehicle concept consisting of three main rigid bodies, a front assembly (front fork), a mid-assembly (passenger cabin) and a two-wheeled rear-assembly (engine, rear part of chassis including rear suspension, wheels, etc.), see figure 8.
As discussed in [5] and [6], the driver steering input torque has to balance both the tilting torque plus a torsional stiffness connecting the cockpit with the rear assembly of the vehicle, and a front wheel steering torque plus an anti-powersteering to initiate cornering from straight-on driving.
Important criteria for the designer are a stable behaviour and, on the other hand, a smooth, responsive cornering performance. As it turns out, various eigenmodes related to yaw, steering and roll behaviour of the vehicle are working against each other in this respect. Obviously, many vehicle design parameters play an important role here which have a major impact on the vehicle behaviour. One might distinguish the overall dimensions, mass distribution, front-fork geometry, tyre characteristics, suspension layout, the tilting controller design, etc.

In [5], the sensitivity of the vehicle performance was investigated regarding changes of the vehicle design, under steady state conditions (i.e. following a circular path). Major effects were observed for varying torsional stiffness as well as for the antisteer control. It was observed that antisteer control had no effect on driver feedback but merely reduced the required driver input for the same steady state cornering behaviour. Quite the opposite was observed for the stiffness of the torsion bar.
Important vehicle parameters effecting the cornering behaviour were found to be the position of the mass centre, the tyre characteristics and the additional weight of one passenger.

Considering the dynamic behaviour, one observes two dominant oscillating eigenmodes, with resonant frequencies ω around 10 and 100 rad/sec (1.7 and 15.9 Hz respectively).
The low frequency mode corresponds to a behaviour of the vehicle with a dominant yaw rate and lateral velocity being in phase difference of 90^o, and with the steering angle in phase with the lateral velocity. That means that the vehicle is in a kind of fish-tail motion, and we'll refer to it as the *Yaw Mode*. The high frequency oscillating mode shows a yaw rate and lateral velocity being almost in phase, with a 90^o phase difference with a dominant steering angle behaviour. We'll therefore refer to this second mode as the *Steering Mode.*

We have further investigated the sensitivity of the vehicle stability regarding changes in vehicle design parameters as well as in the parameters characterising the tilting system. It is to be expected that parameters like masses, tilting axis orientation, positions of mass centres, tyre cornering stiffnesses and camber stiffness are the major contributions to the Yaw Mode. The Steering Mode is mainly effected by parameters related to the front fork such as rake angle, cornering stiffness front, distance between front mass centre and steering axis, and the steering damping. To illustrate these sensitivities, we'll treat the impact of changing the tilting inclination angle μ while maintaining the height of the tilting axle at the connection with the rear assembly at the same level. With positive angle, the steering axis is pointing downward (from aft to for). That means that under cornering conditions, for increasing μ, the front wheel is forced to move more inside the curve reducing the tyre forces. Hence, it corresponds to more understeer or less oversteer which stabilises the vehicle. On the other hand, the tilting inertia of the cockpit plus front fork is increased, leading to lower eigenfrequencies and reduced damping, i.e. corresponding to a destabilising effect. For a tilting axis close to pointing through the cockpit mass centre, the first effect is expected to be dominant. For a tilting axis close to pointing through the front wheel contact point, the second effect is expected to be dominant. Starting from a reference vehicle with μ=0, the effect on the pole connected to the Yaw Mode is illustrated in figure 9 (root locus plot) of 120 km/h.

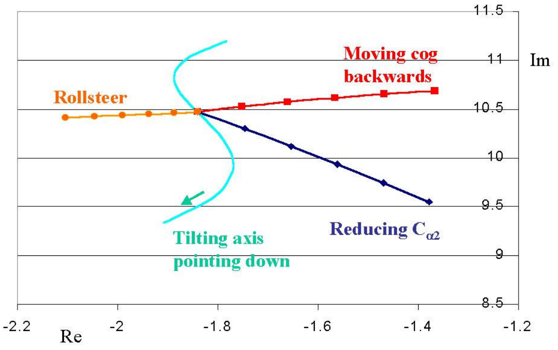

Figure 9: Sensitivity of root locus Yaw-Mode

This figure shows the destabilising effect with the tilting axis pointing downward within a certain range, due to increasing inertia. The resonant frequency is shown to reduce with increasing μ. For large absolute value of μ, the understeer effect becomes the dominant factor.

In the same figure, the impact of rollsteer (rearward steering due to load transfer), lower cornering stiffness at the rear axle, and horizontally moving the vehicle mass centre is shown. Rollsteer and moving the mass centre forward will increase the stability without effecting the resonant frequency significantly. Variation in cornering stiffness effects both the damped natural frequency and the absolute stability.

The response of the NTV has also been determined for a step input in the driver input torque such that a lateral acceleration is reached of 4 m/s^2. The transient response for a step in the input torque is not the same as defined in ISO 7401, where an input steering angle is prescribed. In order to reach such a step-input in the steering angle, the driver input torque needs to exceed the steady state value at the start of the transient manoeuvre (to overcome the inertia of the cockpit). Calculations have been carried out for 80 km/h.

One observes a quick response in the tilting torque with a local overshoot to initiate the tilting of the cockpit. With tilting damping present, this overshoot would show a steeper descent beyond this first maximum. The yaw rate starts with a small delay of about 0.2 sec. and then rises quickly to a significant level. Some oscillations are observed due to the low damping of the Yaw Mode. Similar but smaller oscillations are observed in the lateral acceleration versus time, behaving only slightly delayed with respect to the yaw rate. The small delay times will result in a good subjective driver assessment of the NTV handling performance.

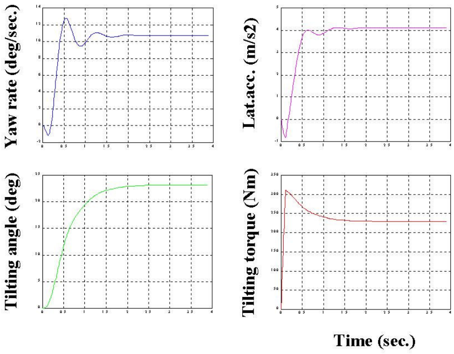

Figure 10.: Step-steer response of the NTV

We have examined to what extent the anti-steer control in the tilting system effects the transient behaviour of the TNV. It appears that the response in yaw rate and lateral acceleration is slightly effected (risetime is increasing) but the main affect is in the tilting torque, being required to roll the cockpit. Without antisteer control, this tilting torque is increased with more then 30 %. That means that more energy is required for this transient behaviour. In other words, the antisteer control serves to derive a better design of the tilting control with lower weights and power consumption.

CONCLUDING REMARKS

A new class of vehicles seem to arise with potential to be used efficiently in nowadays traffic circumstances, with low fuel consumption and with improved safety (compared to motorcycles). These vehicles, presently still introduced as ‘fun-vehicles’ deserve therefore further attention, especially with reference to the existing Intelligent Transport development programs. It is tempting to start an Active Motorcycle Guidance programme (formerly referred to as rider robot), with emphasis on active safety as well as on the complex but therefore very challenging field of vehicle-rider interface.

These vehicles, denoted as Narrow Tilting Vehicles, tilt like a motorcycle during cornering but cannot be compared to motorcycles. Two modes of motion were observed, related to yaw motion and front fork steering stability. Especially the first is observed to have low damping, and the impact of vehicle parameters on the stability properties has been discussed. Parameters like the tilting axis orientation and the roll-steer characteristics of the rear part of the vehicle appear to have a significant effect on the vehicle yaw stability.

Considering the vehicle behaviour in time, typical reference manoeuvres might be investigated. The transient performance shows a rather quick response to changes in driver input torque, compared to passenger cars.

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