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"Tomorrow's Car": Deakin Universities new cross vehicle that combines the best of 2 worlds

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ABSTRACT

Motorbike riders are 34-times more likely to die in a crash compared to car drivers per km travelled (1). Such safety risks together with special skill requirements for the driver and much lower comfort compared to normal cars are the main reasons why motorbikes represent only a fraction of all vehicle sales in developed countries. Deakin University is developing a revolutionary cross-over fun vehicle with ultra low fuel consumption and emissions. This new vehicle generation combines the best of two worlds: the fun to drive, low cost, and small size of a scooter together with the safety, comfort and easiness to operate of a car. The result is a vehicle that is more fuel efficient than most cars or even scooters.

Various tilting cross over vehicles have been presented over the last decade that were trying to automate the tilting control of narrow vehicles to make them safer. Examples of these concepts are the Carver, Clever and in some way also the MP3 scooter from Piaggio. The problem with fully enclosed concepts like the Carver or Clever is that they require very complex and therefore also expensive tilting control systems so that the vehicles are not price competitive compared to low cost micro cars or even normal small cars. The MP3 on the other hand comes with a tilting control system which is only semi automatic so that typical car advantages - comprehensive safety features like crush zones, roll over protection, air bags, safety belts or comfort features like full weather protection including heating and cooling – can not be provided.

Deakin's approach is quite different to the above mentioned concepts. The requirements were derived based on two different investigations: The first step was a critical evaluation of social trends and the second step was an in-depth benchmarking study of existing concepts which identified the typical strengths and weaknesses of these concepts. In a critical next step a new concept was created that addresses most of the weaknesses of existing tilting three-wheelers in a holistic approach by setting clear priority rankings for the vehicle targets, based on current trends. The priorities were set in the following order: Safety, Affordability, Fun and Efficiency (SAFE).

The key feature that enables an enclosed tilting vehicle is a fully automatic tilting control system. With an automatic tilting control system the driver does not need to put the feet on the ground to balance the vehicle when he stops, so the vehicle can be built with a full enclosure. This allows the implementation of typical car like safety features (seat belts, roll over structure, crush zones, air bags). The SafeRide™ tilting control system is a passive system that involves the driver's balancing sense in its feedback control system. The vehicle has typical scooter like steering characteristics, where the steering is initiated through counter-

steering. Another safety critical design feature is the crush zone between the two front wheels which is not possible with only one front wheel or with the powertrain positioned between the front wheels, as the powertrain can't absorb a lot of energy due to its structural stiffness and density. The passive tilting control system is quite simple and therefore makes the vehicle very affordable, an important factor for successful commercialisation.

Another advantage of integrating the human balancing senses in the feedback control of the tilting system is that the system kicks in slightly after the human balancing reacts. In some instances that can generate the typical adrenalin thrill known from riding a bike. This fun factor is quite common with many trend sports like mountain biking, surfing, roller-skating, snowboarding, or skateboarding. Some of these sports have seen very rapid growth only a short time after they have been invented. Utilising the human balancing system during driving also makes the vehicle safer as the adrenalin is produced after reaching a semi-stable driving condition that is controlled by the vehicles tilting control system, but before the vehicle reaches an unstable driving condition that can not be controlled by the vehicle but only (eventually) by the driver – if he has got the required driving skill and if he is alert enough.

Efficiency superior to most cars and scooters is achieved by the aerodynamics of a fully enclosed body structure in combination with the small frontal area of a typical scooter and the droplet shape enabled by the relatively wide front with 2 wheels and the very narrow tail with only one rear wheel. The passive tilting system also contributes to the extreme efficiency as the system only draws some small electrical power for the electronic control unit. Another feature is a low cost exhaust energy recovery system which is discussed in another paper.

TECHNICAL PAPER

INTRODUCTION

Apart from the global financial crises some of the most important challenges for the automotive industry today and even more so tomorrow are global warming, the paralysis of most mega cities, and to some extend peak oil. Some of the first measures that have been implemented to mitigate global warming are CO2 emission limits, for example in the European Union. Mega cities have been and are growing continuously, but parking space in the centres of these very large cities is getting less due to further developments. The result is an increase in traffic jams that waste precious energy, contribute to unnecessary emissions and waste the time of the people involved in these jams, leading to more tension and aggression on the roads. At the beginning of the 20th century the situation in cities was quite similar: horses were the main means of transportation with the negative side effect of severe pollution through horse excrements. Motorised passenger cars were the solution of the problem in these days. Over the last hundred years the basic configuration of most passenger cars has not changed a lot: four wheels, one on each corner, provide very good stability and one or more rows with two or more seats in between these wheels to carry the driver and passengers. However, the transport requirements of today's people in large cities are quite different than hundred years ago because most people drive their car alone when they commute to and from work. Motorbikes, scooters and bicycles are alternative and efficient means of transportation that also are a lot fun to drive – or better to ride. But the negative side of these vehicles is that they are much less safe due to the lack of crash zones, roll over protection and other typical car type safety features like air bags and safety belts.

Therefore a new type of vehicle is required that will satisfy the needs of today's people in large cities. "Tomorrow's Car" for today's people from Deakin University is a new revolutionary cross-over fun vehicle with ultra low fuel consumption and emissions. This new vehicle generation combines the best of two worlds: the fun to drive of a scooter, low cost, and small size together with the safety, comfort and easiness to operate of a car. The result is a vehicle that is more fuel efficient than most cars or even scooters. An image of how such a vehicle could look is shown in figure 1.

Figure 1: A possible design version of "Tomorrow's Car", two of them sharing one bay

MARKET TRENDS

The requirement for a new narrow cross over vehicle has been identified when the author spent much time during traffic jams on the way to work some years ago in Germany even though the travel distance was only 17km – most of it Autobahn - the travel time was around 40 minutes for one trip. Motorbikes or scooters were considered as an alternative but were disregarded to the safety risks involved, lack of rain protection and the limited luggage space. Other factors that played a minor role in that decision were the requirements for special safety gear and to wear a helmet. Extra safety gear would result in excessive transpiration during summer (not ideal for a typical business work environment) and wearing a helmet would limit the options for hairstyles (the latter problem is negligible now due to the loss of hair). So the journey started in the search to find a viable alternative and the first step was to analyse current market trends firstly to back-up the initial individual thoughts with solid data and secondly to identify other opportunities that could be satisfied with a novel vehicle concept, so that a successful commercialisation can be ensured.

Safety

Over the last couple of year safety has been considered the third most important car consumer purchasing criteria after quality and fuel economy (2). That corresponds well with Maslow's hierarchy of needs (3), safety is actually the second important layer after physiological needs like breathing, food, water, etc. Additional to health security this second layer also includes resources and one can argue that vehicle quality and fuel economy are also securing resources and therefore are part of the same layer of need. Consequently the development of new safety features has constantly been a priority in the automotive industry that helped to reduce fatality rates over time. Examples of such new safety features include safety belts, head rests, anti lock brake systems, electronic stability systems, tyre pressure monitoring systems, etc. Often these features have been made part of safety regulations so that their fitment became mandatory. Enhanced safety standards and test procedures like the NCAP test support the drive to develop new safety features for cars.

After World War 2 motorbikes were considered as a cheap alternative means of transportation, the associated higher safety risks compared to cars were of second priority due to the limited financial resources available. That has changed since then and nowadays most motorbikes – at least in the western world – are considered to satisfy needs on the top layers of Maslow's pyramid of needs: self actualisation and esteem. Motorbikes are considered to be more a piece of sport equipment - similar as horses - than a transport vehicle.

Compared to cars the development of new safety features seems to be of a much smaller priority even though some new safety features have been introduced like anti lock brakes and electronic stability control systems. But there are no standardised crash tests to evaluate and compare the safety of a motorcycle in a similar way as they are for cars. This is a bit of a surprise because motorcyclists were about 34-times more likely to die in a crash compared to car occupants per km travelled (1). And the trend is going into the opposite direction than for cars as the fatality rate for motorbikes has actually increased year after year between 1997 and 2004 "making up 9.4% of all motor vehicle traffic fatalities " in 2004 (1).

A similar trend could be seen in relation to All Terrain Vehicles (ATV), they are the biggest cause of child fatalities on farms in Australia (4). In the USA 6500 ATV related deaths were reported between 1982 and 2003, and 704 in 2004 of which 31% were under 16 years of age (5). The main reasons were: Colliding with fixed objects, Vehicles rolling over onto rider/passenger and Colliding with other vehicles. Root causes are shown in figure 2.

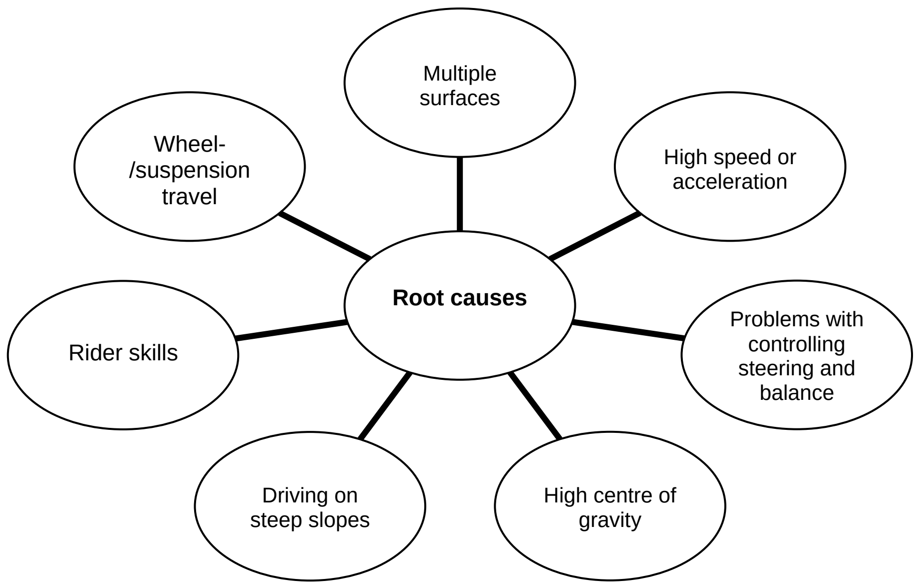


Figure 2: Roots causes of fatal ATV's accidents (5, 28)

So there is a strong need to improve the safety of motorcycles and ATV's. The introduction of standardised safety tests like NCAP together with the continuous independent testing and publication of results has been a big driver to improve car safety. Maybe it is time now to develop and standardise similar tests for motorcycles. There could be several reasons why that has not happened so far: first of all the number of motorcycle riders is much smaller around only 10% compared to the number of car drivers, depending on the country. Secondly the layout of most motorcycles – no roof and no back rest – make it very difficult to install typical car like safety features like crush zones, roll over protection, air bags, etc. First attempts have been made with the C1 from BMW. Unfortunately these additional safety features also increased the centre of gravity and made the vehicle more difficult to manoeuvre and it reduced its performance compared to scooters with similar powerful engines. Therefore the production was ceased after only a short time. Thirdly the motivation to ride a motorcycle often is more driven though higher layers of the Maslow pyramid (self actualisation and esteem) instead of safety, similar to participants in trendy fun sports, for example skateboarding, snowboarding or roller blades.

Affordability

According to KPMG (2), affordability is the fourth most important consumer purchase criteria since 2005, after quality, fuel economy and safety. In 2008 it was even rated the third most important consumer purchasing criteria in the 2009 KPMG Global Auto Executive Survey (6) which probably reflected the beginning of the global financial crisis. That means that even if a product offers certain advantages the surcharge needs to stay within a certain limit, otherwise it won't find enough customers and it won't make a business case so that the production would need to be ceased, some examples will be discussed later in the benchmarking section.

Fun

New trendy fun sports are emerging every year, may it be surfing during the 1960's, windsurfing and skateboarding in the 1970's, mountain biking and snowboarding in the 1980's, rollerblading in the 1990's, kite-surfing, rip-sticks and so on. There are several similarities between all these trend sports (compared with normal transportation like walking or driving a car):

- They provide additional fun and thrill while the body is leaning sideways into the third dimension and experiencing additional centrifugal force added to the force of gravity
- They are outdoor activities, mostly performed in free nature
- They involve a significant element of risk and it takes a while to learn them
- New pieces of sports equipment are required with costs of up to several thousand dollars involved which often create new sport industries.

So the biggest question is what is coming next ?

Efficiency

There are several drivers that require vehicles to become more fuel efficient: the first one is a simple business case to reduce overall costs for the consumer. The business case is illustrated in figure 3. Savings for fuel costs are displayed for different fuel prices as a function of the mileage for the example of an average fuel consumption reduction of 1 l/100km. Even though the graph shows Australian Dollars, the graph is also valid if the currency is changed, for example to Euros. It shows that over the typical life time mileage of a vehicle the consumer can save between around $1,500 and $3,000 on fuel depending on the actual cost of fuel. So if the cost for the technology to reduce fuel consumption by 1l/100km would be $150, the consumer will start to make a positive return on that investment after around 6 months or maximum one year. This business case with the main factors cost of fuel, cost of fuel saving technology, and yearly mileage were the key drivers for the high market share of Diesel vehicles in Europe.

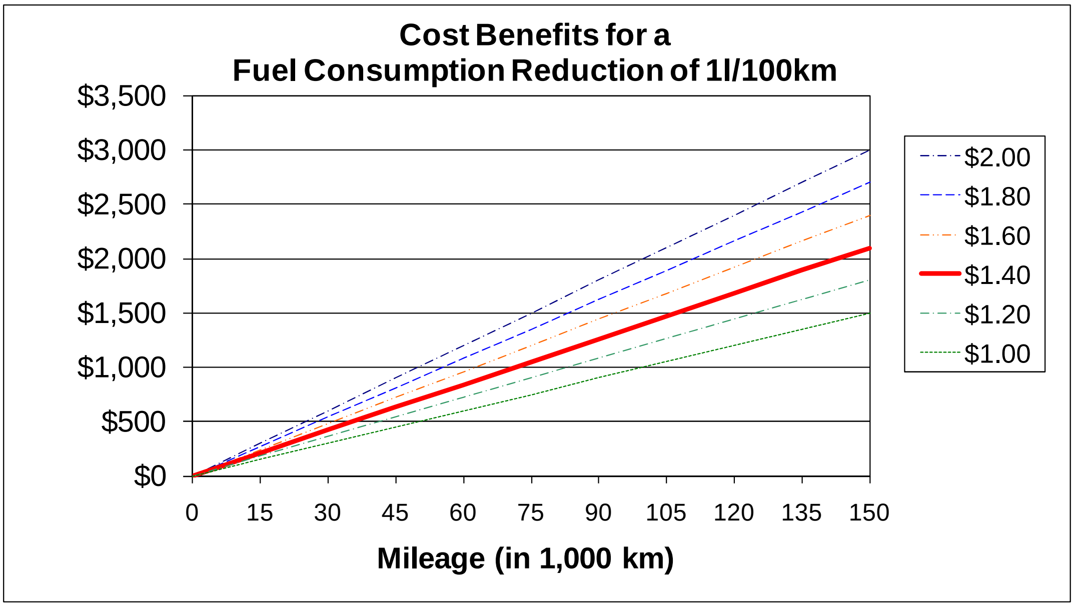


Figure 3: Savings for fuel based on different fuel prices as a function of the mileage for the example of an average fuel consumption reduction of 1 l/100km

Global warming has resulted in CO2 emission regulation related to transport vehicles. This has enhanced the previous business case dramatically. For vehicles that won't meet the new targets tax penalties of up to Euro 95 for each gram CO2 per km need to be paid by the car manufacturers for each vehicle for the amount of CO2 emissions that will exceed its limits. For a vehicle with a gasoline engine that exceeds the limit by the equivalent of one litre/100km that could result in a tax penalty of Euro 2,280. So from the time when the new regulation applies the business case for more efficient vehicle is more than ten times as strong compared to now: a fuel saving technology that reduces the fuel consumption by one litre/100km can cost more than Euro 2,000 and delivers still a return on investment already when sold and not just after a year !

Traffic Congestion

To find a spot to park a car in cities becomes also more and more difficult and in parallel the prices to park a car is also continually growing which is another factor that influences customers to prefer smaller cars compared to large cars as smaller cars are also easier to manoeuvre in parking garages. Increased traffic congestion is a direct consequence of the growing vehicle fleet and the increased distance travelled per vehicle: "In 2003 - 2004 alone, the passenger vehicle fleet on Australia's roads increased by three percent or around 260,000 extra vehicles nationally" (7). "The OECD has prepared projections which indicate that, between 1990 and 2030, there will be an increase of 79 per cent in kilometres travelled by all vehicles within the OECD countries, and a rise of 312 per cent for countries outside the OECD (OECD 1996)" (8). This indicates that this is a trend that will prevail for a longer time so the traffic congestion problem is more likely to grow.

Parking Space in Cities

The previous trend only relates to traffic in general but what is even worse is that most of that traffic growth is actually predicted for cities. Today "urban areas already account for 50% of the world's population, but 80% of the world's wealth" (9). "By 2030, urban areas are projected to account for 60% of the population and greater than 80% of the wealth "(9). This is going to paralyse many mega cities so that the advantages of individual transportation with motor vehicles will diminish rapidly. The average speed in the Greater Tokyo Area is already down to 15km/h reported in 2008 (10).

Average Car Occupancy

The average car occupancy for journeys to work is only somewhat higher than 1, actually only about 1.2 according to Public Transport User Organisation (PTUO) (11), and in the US it is the same even considering all times usage (12). Considering that most families have two cars where one at least is only used for one of the partners to drive to work, this means that a vehicle with only two seats would be sufficient to solve the needs of at least of 50% of the passenger car drivers. This means that most of the existing passenger cars are absolutely oversized compared to the needs of their users.

Engine Performance

Engine performance of passenger cars on the other hand is continuously increasing: the physical ACAE fleet characteristics showed a 22% higher power in 2002 compared to the baseline of 1995 (13). This is very interesting as more powerful engine normally use more fuel to operate which is not helping to achieve the commitments to reduce CO2 reductions. A reason might be that people may think they could make up lost time in traffic congestions with more powerful engines or that they just want to be able to have more fun while accelerating hard in during the limited occasions when there is no other car in front of them. This trend to more engine performance was even stronger in the US where the average engine performance almost doubled between 1985 and 2004 (14).

Drivers Licence

In Germany for example 84 percent of adults possess a driving licence and the proportion of female driving licence holders has grown to 76 percent (15). The numbers of motorcycle licence holders is only around 14% compared to the numbers of car licence holders (16) and the share of female riders is again only around 14% (17). One of the reasons is obviously the increased safety risk but another factor is that the costs to obtain a motorcycle license which could be twice compared to a car license (17).

Based on these important trends the requirements for a new generation of vehicles can be summarised into the following: There is a strong business case for ultra efficient environmental friendly vehicles that offer a new dimension of fun compared to motorbikes, they should be as small as possible so that lanes and car park space can be shared and they should have at least 2 seats and offer a safety compared to a car. But it still should be reasonable powerful and only a car driver's license should be required.

BENCHMARKING OF NARROW VEHICLES WITH TILTING CONTROL

To learn from the lessons that were made during the introduction of other novel cross over vehicles an intensive benchmarking study was conducted. The idea was to identify criteria that are important for a successful commercialisation and to also identify killer criteria that could prevent a commercial success. Together with the analysis of the market trends that would be an additional sanity check.

Vehicles that were considered similar to “Tomorrow’s Car” are small narrow vehicles with one or two seats that are able to lean sideways.

These vehicles were evaluated with the following two tables. Table 1 compares the technical data such as the main dimensions, weight, top speed, acceleration, fuel economy and price. To calculate a simple cost per value ratio, a formula has been developed which is based on top speed, number of passengers (1 or 2 if the number of seats is bigger than one to reflect the fact that the average passenger loading is only around 1.2 anyway so most consumers will be able to accommodate all mobility needs for urban commuting with 2 seats), price and fuel economy assuming a fuel price of $1.40 per litre. It calculates the total costs by adding retail price and lifetime fuel costs, which are divided by the top speed and the number of seats. The lowest number means the lowest cost per value, or the best value for money. Finally the production status is listed (under development or already in production).

Table 2 includes a very simple subjective assessment of how each concept addresses the important trends that were discussed earlier. A rating of 3 means the trend has been addressed very well, where a rating of 0 means that the trend has not been accounted for. At the bottom all ratings are added and, with the highest number indicating the best concept, representing the highest number of trends addressed. This leads to a ranking from number one the best concept, two for the second, and so on.

“Tomorrow’s Car” has been included in this evaluation so the results of the concept definition, the subject of the next sub-heading, have been used to compare this with the benchmarking results, so a reader can easily compare.

The most similar vehicle compared to “Tomorrow’s Car” is the Clever concept (Compact Low Emission Vehicle for Urban Transport (18)) with a trend score of 23 – which is the second place - and CVR of 83 $/kph – also the second place. It is a narrow three wheeler where the front wheel and the main body are tilting controlled by a specially developed active hydraulic system. The powertrain is placed between the two rear wheels, that part is not tilting. Therefore for this non-tilting part similar dynamic requirements apply as for a normal car. Advantages are the low price target and the outstanding fuel economy target. The disadvantages are the low performance (a top speed of only 100km/h) and safety risks. These safety risks were well known by the Clever team, this is the reason why they were starting with crash tests even before demonstrating the tilting mechanism. There are basically 3 potential safety risks:

- Frontal Crash test: the front wheel could intrude into the passenger compartment and hurt the drivers legs
- Instability with strong side winds
- Instability during bends in combination with emergency braking

The active tilting control system seems to be quite complex and a little similar to the Carver system. Therefore the cost target seems to be very aggressive, and it is questionable if it can be achieved. A prototype has been built but there are no indications on the web site about any further production plans.

Another similar vehicle is the Carver (19). The trend score is 19 which means 6th place and the CVR is a very expensive 185 $/kph which is only the second last place from the 8 concepts studied. The Carver is a similar concept to the Clever. The distinctive advantages are the higher performance and top speed. Significant disadvantages are the width of between 1.3m and 1.6 m so it still requires a similar space as a normal car does, the high fuel consumption not better than an efficient small car and the very high price. The safety concerns are the same as for Clever plus that it is so much fun to tilt and there is no physical feedback to the driver about the physical limits compared to a car or a motorcycle so an enthusiastic driver easily tends to provoke it to tilt, even on straight roads. Around 200 Carver's have been sold but unfortunately production was discontinued in 2009 as the price was too high (20).

The last comparable concept on the list is the Ecomobile. It is operated as a motorbike with two main wheels and one support wheel on each side that only touches the ground at low speeds or as the driver requires. The vehicles are all handmade using aerospace technology, around 100 vehicles were built between 1987 and 2005 and recently has been replaced by a new model called Monotracer (21). Consequently it is an extremely expensive product leading to the highest CVR of 232 $/kph which is the last place, the same as for the trend score which is only 17. This is caused by its main disadvantages, firstly the very high price. Other issues that prevent a wider market acceptance are the need for a motorcycle driving licence in combination with special training as it feels very awkward when the operation is switched from two wheels to 4 wheels and vice versa which is a major safety concern. The vehicle is still very wide and the fuel consumption is also relatively high due to its high performance. The biggest advantage is the fun to drive leaning sideways together with a very high performance.

Feature	**Unit**	**Clever**	**Ecomobile**	**Carver**	**Smart**	**Fiesta**	**C1**	**MP3**	**Tomorrows Car**
Width	m	1	1.475	1.4	1.515	1.8	1.026	0.76	0.795
Length	m	3	3.7	3.4	2.5	3.924	2.075	2.035	2.5
Height	m	1.4	1.475	1.3	1.549	1.468	1.766	N/A	tbe
Weight	kg		440	670	730	1056	185	221	450
Tyre size	inch	17	17	17/15	15	15	13/12	12	17
Fuel Consumption	l/100km	2.2	5.4	6	4.7	6.6	3.2	4.4	2.5
CO2 Emissions	g/km			177	113	156	66	108	61
Top Speed	km/h	100	240	185	135	184	112	110	140
Acceleration 0 -100km/h	sec		6.2	8.2	15.5	11			10
Seats	-	2	2	2	2	5	1	2	2
Price	A$	12,000	100,000	56,000	19,900	16,900	10,000	12,000	15,000
Lifetime fuel costs	A$	4,620	11,340	12,600	9,870	13,860	6,720	9,240	5,250
Fuel price	A$/l	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Life time costs	A$	16,620	111,340	68,600	29,770	30,760	16,720	21,240	20,250
Performance related Lifetime Cost per Passengers (max. 2)	**A$/(km/h)/ passenger**	**83**	**232**	**185**	**110**	**84**	**149**	**97**	**72**
Ranking	-	2	8	7	5	3	6	4	**1**
Status	-	Prototype	Hand Made Production	Discontinued	Mass Production	Mass Production	Discontinued	Mass Production	Planning

Table 1: Cost per value assessment for different vehicle concepts

To highlight some important issues, three other vehicles have been included in this comparison. The first one is the Ford Fiesta as an example of a typical small car that has been mass produced successfully and still is (22). The trend ranking of 22 means third place, very close to the Clever, and with a CVR of 84 $/kph, the Fiesta is also third.

The next interesting car on the lists is the Smart (23). The reason why the Smart has been chosen was that it is also a relatively new concept to address the needs of urban commuting, mainly a smaller footprint for parking. The approach was to reduce the car length instead of the width. The advantage of that approach is that conventional car technologies could be used for the chassis and suspension and no tilting control is required. Disadvantage are that the space advantage can only be used in some dedicated car parks, if parked in a normal car park where cars park in parallel, the advantage of the small footprint can't be utilised because a second car would lock the first car in the same standard car park. Also the aero dynamical drag factor suffers due to the reduced length and the driving dynamic at higher speeds and uneven ground feels very uncomfortable, therefore the top speed has been restricted to 135km/h. The result of the trend assessment is a score of 20 which means a solid 4th place and a CVR of 110 $/kph or 5th place. The lower CVR ranking is mainly caused by the relatively high price in combination with the low to speed.

	Rating: 3 - very well adressed, 0 - not adressed							
Trends Addressed	**Clever**	**Ecomobile**	**Carver**	**smart**	**Fiesta**	**C1**	**MP3**	**Tomorrows Car**
Global Warming	3	1	1	1	0	2	2	3
Fuel Prices	3	1	1	1	0	2	2	3
Fun (Leaning Sideways)	3	3	3	0	0	3	3	3
Performance	0	3	3	1	2	0	1	2
Parking Space	2	1	1	1	0	3	3	2
Passengers	1	1	1	1	3	0	1	1
Car Drivers License	2	1	2	3	3	2	2	2
Safety	2	1	2	3	3	0	0	3
Luggage Space	0	1	1	2	3	0	0	1
Comfort	3	2	3	3	3	1	1	3
Complexity / Reliability	1	2	1	2	2	3	2	2
Price	3	0	0	2	3	3	3	2
Total	**23**	**17**	**19**	**20**	**22**	**19**	**20**	**27**
Ranking	2	8	6	4	3	6	4	**1**
Status	Prototype	Hand Made Production	Discontinued	Mass Production	Mass Production	Discontinued	Mass Production	Planning

Table 2: Trend assessment

The C1 scooter from BMW is partially encapsulated with a windscreen, wiper, roof, and car seat with safety belts which was aimed in much better safety compared to a normal scooter. However safety was also one major disadvantage compared to the other vehicle that were evaluated: it has a high centre of gravity in combination with small wheels which makes it difficult to manoeuvre at low speeds or over little obstacles like a curb stone, specially for smaller people. So people had to attend a special training course and even during the press launch one journalist fell off at 0mph and needed medical attention to his knee (24). The trend score of only 19 meant sixth place, same as for the CVR ranking with 149$/kph. The high CVR indicates the price was very high for the relatively low performance and the limited seat number of only one. This was certainly one of the reasons for BMW to stop production after only 2 years as sales dropped very quickly after a quite successful launch in the first year of production.

Finally the Piaggio MP3 was evaluated, a scooter with 2 front wheels and one rear wheel with a semi-automatic tilting lock function. Compared to a normal scooter the advantages of the 2 front wheels are better braking performance and higher stability on slippery ground, particularly when one front wheel loses traction (25). It returns a quite good trend score of 20 which is 4th place together with the Smart. The low CVR of 97$/kph also means 4th place. However, its disadvantages compared to fully encapsulated vehicles are still safety related. Although it has much better stability against roll over compared to the C1 it offers much less crash protection.

It is interesting to notice that the rankings from the trend evaluation and the CVR score were almost identical. There were only two differences in the rankings (for the Smart and Carver) and they were caused by two equal rankings in the trend score (Smart and MP3 both 4th, and both discontinued vehicles Carver and C1 on 6th). That indicates that the CVR offers a better resolution in assessing these kinds of new vehicle concepts and it is much easier and faster to perform with less chances for variability due to the subjective nature of the trend ratings.

In comparison "Tomorrow's Car" ends up as the number one concept for both assessments, with the best cost-value ratio (CVR) of only 72 $/kph and addressing all trends with a top score of 27. It should be mentioned though that the results for the Clever and "Tomorrow's Car" are only targets so far, that need to be verified under typical mass production conditions. However, the dominance of "Tomorrow's Car's" scores is quite large with 15% advantage in both, the CVR rating and the trend score, compared to the second best concept. So even if the actual production cost would vary a little or if some performance targets would need to be adjusted there is still quite a big safety margin.

CONCEPT DEFINITION FOR "TOMORROW'S CAR"

A step by step approach has been taken to define the concept of "Tomorrow's Car". Targets for several features and dimensions are shown in table 1. The vehicle had to be fully enclosed, a key requirement for car like safety and comfort. The first important decision was about the width of the vehicle. To be able to park two of the vehicles in parallel in one parking bay, the width needs to below one meter, a width slightly below 80 cm has the advantage that the vehicle could also be driven through a door and parked in the hall way, which was a requirement articulated during of a focus group interview. Several more focus group interviews will follow to verify the validity of the concept. Such a small width did not leave to many options for the wheel configurations. Three points are the minimum requirement to define a plane and to enable a stable configuration when standing. So 3 wheels where selected because they are cheaper than 4 wheels with 4 suspensions. Two front wheels are more stable in unexpected critical situations like emergency breaking in corners. They also offer some potential to accommodate extra crush zone in that the feet and legs could slide through the two wheels in case of a frontal crash. Another advantage relates to the aerodynamics; with 2 wheels in the front and one rear wheel a configuration very close to the most efficient tear drop shape can be realised.

The next question was related to the mechanical part of the tilting system. One option was to have the front wheels in a non-tilting configuration similar as the Carver and Clever and another option was for all 3 wheels to tilt as the MP3. Non tilting front wheels would require a very low centre of gravity of the non tilting sub-system otherwise it needs a relatively wide track to avoid roll over during fast cornering. Such a system would make it very difficult to achieve the required targets for the small width in combination with the high performance. Potential patent protection due to similarity with the Carver's technology could be another issue. Therefore a trapezoidal linkage system was selected similar to the one invented by Wolfgang Trautwein in 1976 (26), (27) that was already tested on a Piaggio Scooter in 1984 and is now also used in the MP3. The tilting will deliver the extra fun of a normal motorcycle.

Some of the next decisions were very easy, for example the requirements for 2 seats in a tandem configuration: That satisfies the need to transport more than one person which covers more than 90% of all journeys in cities. It also gives extra secure luggage compartment for shopping, in particular with the flexibility to fold down the rear seat as displayed in figure 4. That was another important requirement from the first focus group interview.

The seats need backrests and headrests similar as the C1, as these features are key enablers of other important safety features like seat belts and air bags. The vehicle height and length are not very critical, a higher vehicle would result in a reduction of fuel economy but it is better for good visibility. A short length is only important if parking on walk ways is considered, like for normal scooters. For parallel parking in one standard bay of typically 5.5m length the vehicle length just needs to be within that limit, like for normal cars. If the vehicle is longer a better aero dynamical drag could be achieved which is better for good fuel economy if the weight maintains constant. Therefore the wheels can have a much larger diameter similar to typical motorbikes instead of the typical small wheels of scooters. Larger wheel diameters enable lower rolling resistance, better performance and comfort and they help to make the vehicle more stable and safe.

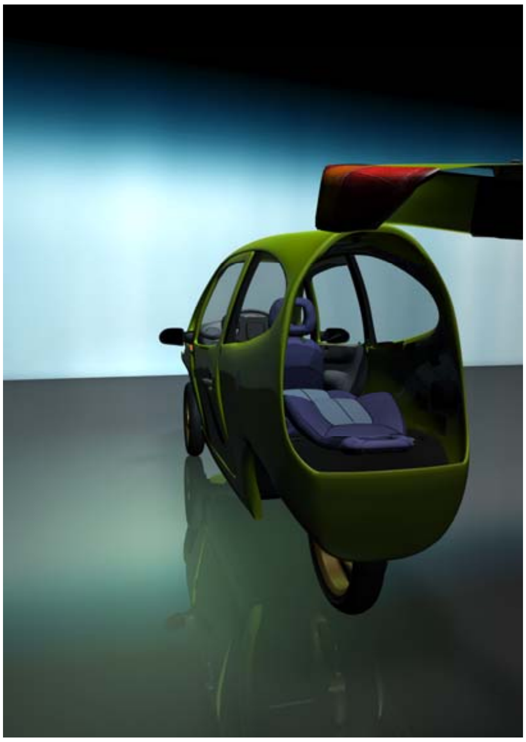


Figure 4: Rear and side view of “Tomorrow’s Car”

The question about the controls was much more difficult to answer: motorcycle controls like a handlebar with throttle grip and brake lever versus steering wheel with throttle pedal and brake pedals? To ensure the vehicle can be driven with a car license the controls had to be as close to a typical car. Therefore brake and throttle are operated through foot pedals and steering is controlled with a “hybrid handlebar”, a mixture between a steering wheel and a handlebar in a rectangular shape as shown in figure 4. A round steering wheel can’t be used as the riding characteristic of a typical motorcycle requires a precise feedback about the actual steering angle. The vehicle has at least 2 side doors so that the passenger could get out and into the vehicle on both sides, another requirement of the first focus group interview. If a vehicle is parked parallel to the road it is preferred to enter the vehicle from the side close to the walk way to avoid potential dangerous interaction with the traffic on the main road. With two doors, one vehicle covers the requirements for markets with left- and right-hand driving. Table 3 shows a summary of how different key features of "Tomorrow's Car" address the most important trends that have been identified.

This vehicle configuration is an ideal platform for an electric platform, much better suited than a normal car because less energy needs to be stored on such a vehicle. There are various reasons for that: superior aerodynamics, low vehicle mass, low range requirement, and low payload requirement. Compared to a normal car the aero dynamical drag is much lower due to the smaller width of only around 50% which halves the effective frontal area. The vehicle mass is also much smaller due to the vehicles smaller size, also only around half of the weight of a normal small car and the same applies for the payload. Because the vehicle's main usage area will be cities, the reduced range due to battery costs and weight are not a problem, same as for a normal scooter that typically only has a range of around 200km anyway.

The key enabler for such a vehicle however is a simple but dynamic fast response automatic tilting control system which is briefly described next.

	Trends Addressed											
Features	Global Warming	Fuel Economy	Fun	Performance	Parking Space	Passengers	Car Drivers License	Safety	Luggage Space	Comfort	Complexity / Reliability	Price
Fully Enclosed	x	x		x				x	x	x		
Narrow	x	x	x		x							
Tilting			x									
3 Wheels	x	x	x					x			x	x
All wheels tilting								x				x
2 seats						x						
Foot pedal controls							x	x				
Steering wheel			x				x	x				
2 doors								x		x		x
Wheel size	x	x	x	x				x		x		

Table 3: Summary of key features and which trend they address

TILTING CONTROL SYSTEM

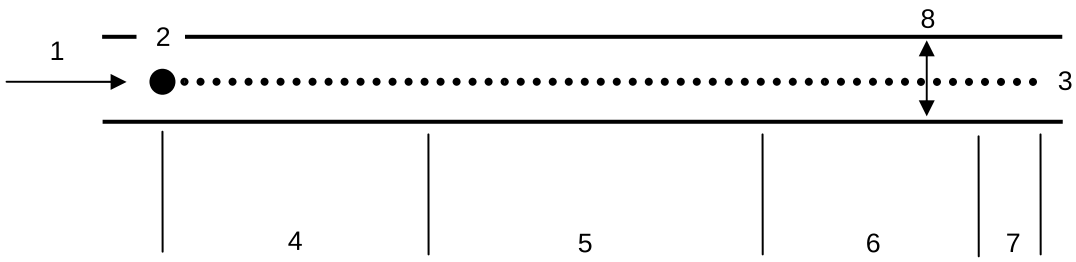
The objective for the new tilting control system was to support as many of the key trends as possible: Fuel consumption had to be minimised, the vehicle needs to be fun and exiting to drive, high performance, package space and weight to be minimised, high comfort and low complexity and cost. The most obvious solution was an active system that applies a force between the tilting frame and non tilting components like a horizontal cross bar as used in Trautwein's trapezoidal system (27). Different types of energy sources would be possible, for example hydraulic, electric or pneumatic. Although pneumatics was considered as the cheapest solution it was disregarded firstly due to the limited controllability and also due to energy losses through to leakages. An active hydraulic system was already proven in the

Carver. However the active hydraulic system with the requirements for many redundancies was one of the reasons that make the Carver so expensive. The Ecomobile also has a hydraulic system which is manually operated but even though it has not got the same requirements for redundancies it also contributes significantly to the Ecomobile's high cost. An electric system was also considered, the Segway uses an active electric balancing system, but this system appears to be even more expensive. So an alternative solution was required. Because a motorbike continuously swings from leaning a little bit from one side to the other, the idea came up to use a passive system that would create the stabilising force in a passive way by dampening the tilting movement.

The development of the tilting control system also started with some analysis of the driving dynamics of tilting vehicles. Different questions needed to be answered: Which signals are suited best to determine an unstable condition ? What are typical thresholds when a scooter rider determines an unstable condition so that he puts the feet on the ground to balance the vehicle ? Can a passive system create enough force that would be sufficient to control the balance of a one three-wheeled tilting vehicle ?

<u>Signals</u>

To find out which signals are suited best to determine an unstable condition an MP3 vehicle was instrumented with various sensors that could measure the following signals (28): Yaw Rate, Roll Rate, Steering Angle, Steering Rate, Steering Acceleration, Roll Angle, Roll Rate, Roll Acceleration, Vehicle Speed, Accelerations in x-, y- and z-direction. A simple test track was defined as a straight line with different zones as displayed in figure 5. Tests were conducted with a passenger who was instructed to introduce a severe side movement of an arbitrary direction not know by the driver in section 2 of the track. Immediately the driver had to react to this disturbance to get the vehicle back under control again. Tests were conducted with 2 different drivers each of them with different motorcycle driving experience and with 3 different passengers of different weights.



Key

1	Driving direction	5	Section 2
2	Start position	6	Section 3
3	Driving line	7	Section 4
4	Section 1	8	Width of track

Figure 5: Test Track (28)

The disturbance input through the passenger was measured as well by an accelerometer. All signals were recorded time aligned and analysed. Figure 6 shows an example signal plot. The result of that analysis was that the signals with the fastest response following the disturbance signal was the steering angle acceleration followed by the steering angle rate and the acceleration in y-direction.

Tilting Thresholds

The tilting thresholds were determined on the same track. The difference in the instrumentation was that the acceleration of the feet was measured to find out at which conditions the driver was starting to move the feet to support the balancing. This test was conducted with 4 different drivers each of them with different motorcycle driving experience. The results showed critical roll angles between around 1 degree up to a maximum of almost 5 degrees and typically lower maximum angles for the experienced rider and also a smaller variation for the experienced rider (figure 6).

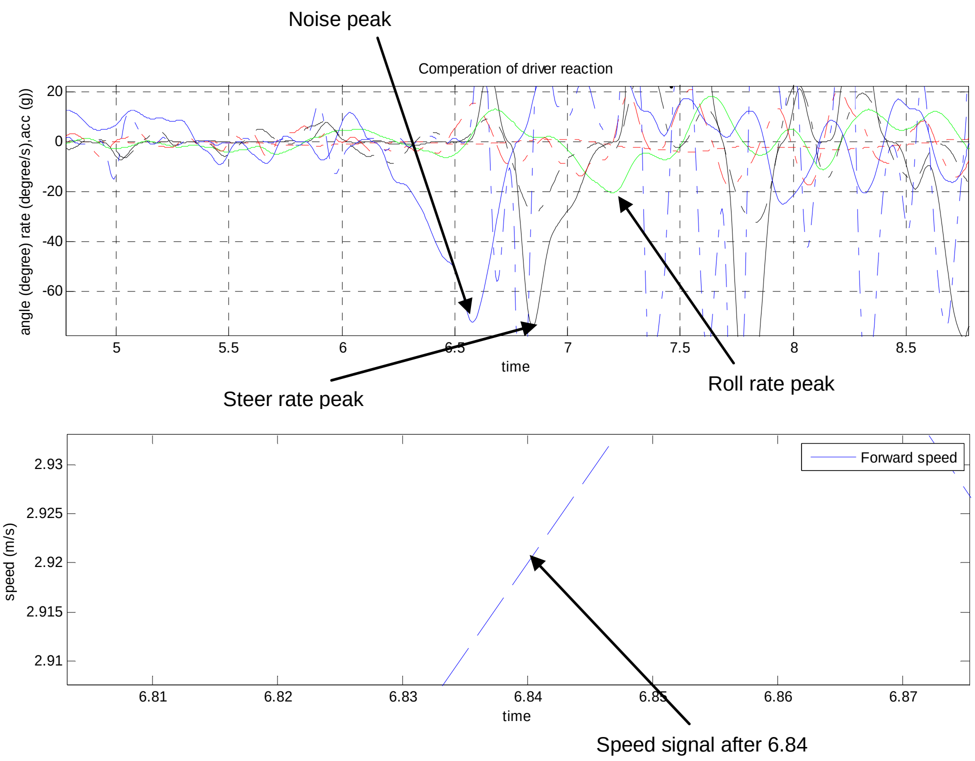


Figure 6: Signal responses after a disturbance (28)

Passive Forces

The verification if passive damping forces are sufficient to control a tilting vehicle at a speed of 0km/h was the most critical step in this investigation. For this purpose 2 double acting hydraulic cylinders were mounted on the MP3 parallelogram as illustrated in figure 7, the original semi-automatic control system was de-activated and partially removed. The cylinders were connected with a relatively simple hydraulic system with several valves. The side view shows the system after stabilisation with the SafeRide™ tilting control system.

In fully locked condition the forces were measured that were required to roll the vehicle over in both directions. This critical tilting force was around 200N at the handlebar which is equivalent to around 1000N at the hydraulic damper in its operating direction. At zero degree tilting angle each damper can transfer a maximum force of 1075N at zero tilting speed, that means that the SafeRide™ system has built in a double redundancy and is able to stabilise the vehicle with only one of these hydraulic dampers.

Figure 7: MP3 tilting system replaced with Saferide™ system with hydraulic cylinders, front and side view.

First tests have been conducted where the tilting system was manually locked while the vehicle was leaned to the side. Then the tilting control system was activated and the vehicle was excited to move upright, either from a rider sitting on it moving sideways or through a person from the side giving it an upwards push. The system unlocked itself and locked automatically in the upright position.

SUMMARY

Deakin’s “Tomorrow’s Car” is a novel cross over vehicle that addresses many current trends like safety, affordability, fun, fuel economy, traffic congestion, limited parking space in cities, low average car occupancy, performance needs and driver license considerations and requirements. The heart of “Tomorrow’s Car” is a novel passive tilting control system. A first analysis has demonstrated the viability of that system. The next step will be the fine tuning of the control system algorithm as well as a more detailed market research study.

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REFERENCES

(1) National Highway Traffic Safety Administration (NHTSA),"2006 Motorcycle Safety Program Plan", NHTSA, 2006
(2) Uwe Achterholt, "Momentum KPMG's 2008 Global Auto Executive Survey", KPMG, 2008
(3) Abraham Maslow, "Motivation and Personality", Harper and Row Publishers, 1954
(4) Australian Centre for Agricultural Health and Safety, National Farm Injury Data Centre, Farm Injury Newsletter Issue 20, July 2005
(5) US Consumer Product Safety Commission, 2004 Annual Report of ATV Deaths and Injuries, September 2005
(6) Uwe Achterholt, "Momentum KPMG's 2009 Global Auto Executive Survey", KPMG, 2009
(7) AAMI, "NATIONAL MEDIA RELEASE", AAMI, September 2005
(8) Ainsley Jolley,"New Technologies, Industry Developments and Emission Trends in Key Sectors: The Land Transportation Sector Draft Working Paper No. 1", Climate Change Project, Climate Change, Industrial Structure and the Knowledge Economy Working Paper Series, September 2004
(9) Dr. A.M. Lippert, Dr. Gary J. Smyth General Motors R&D and Strategic Planning, Warren MI, USA, "Global Energy Systems in Transition: Next Steps in Energy Diversity for Transportation", International Vienna Engine Symposium ,2009
(10) Marton Pettendy, "Road", Goautomedia, 2008
(11) PTUA, "Common Urban Myths About Transport", Public Transport User Organisation, 2006, http://www.ptua.org.au/myths/carpool.shtml
(12) Robert Riley," Alternative Cars for the 21st century", SAE, 2003
(13) Monitoring of ACEA's commitment on CO2 emission reductions from passenger cars (2002), final report 2003
(14) Theodoros Zachariadis, "On the baseline evolution of automobile fuel economy in Europe", Elsevier, Energy Policy 34 (2006) 1773–1785
(15) VDA, "Auto Annual Report", VDA, 2005
(16) KBA, "Fahrerlaubnisse - Fahrerlaubniserteilungen Jahr 2008", KBA, 2008
(17) P.C. Noordzij (SWOV), E. Forke (IfZ), R. Brendicke (IfZ) & B.P. Chinn (TRL), "Integration of needs of moped and motorcycle riders into safety measures", SWOV, 2001
(18) http://www.clever-project.net
(19) Carver Europe BV, "Carver One – Specifications", www.carver-europe.com, year unknown
(20) Jeremy Korzeniewski "Carver Europe files for bankruptcy, technology may live on", Autobloggreen, 2009

(21) http://eco.peraves.ch/ndexe.htm
(22) Ford, “Fiesta specifications and options”, Ford, 2005
(23) smart, “smart fortwo coupé & cabrio”, www.smart.com, 2007
(24) Jeremy Clarkson, “ BMW C1”, The Sunday Times, April 23, 2000
(25) Piaggio, “MP3 125-250ie Technical Training”, Piaggio, year unknown
(26) Michl Koch, “Das besondere Dreirad - Der schräge Otto, Motorrad 02/1984
(27) Wolfgang Trautwein, “Stabilised Three-Wheeled Vehicle”, US Patent 4020914, 1977
(28) Marcus Erbert, “An Unique Arrangement of Sensors and Actuators that Build a Rapid Control System, Ino8 Pty Ltd, 2008
(29) Grant Greenaway, “Design & development of a tilting control system for narrow vehicles”, Ino8, 2008