Analysis of a construction solution for narrow track vehicle (NTV)

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Abstract. At present, automotive industry and as well as car drivers are faced with increase of new challenges such as new emission limits, increased traffic congestion and reduced parking spaces in cities. All these challenges are leading to changes in consumer preferences and the requirements for modern passenger vehicles. The basic layout of today’s car has not changed much since its invention and it is not suited to solving today’s problems. An average conventional vehicle is still four wheeled box growing bigger every year. In Europe and the US, the average number of occupants of a single vehicle is about 1.52. It is clear that the current vehicle size is highly underutilized. The cities are getting more and more congested due to the use of motor vehicle for commuting. Building highway infrastructure at the same growth rate as a number of vehicles is not a feasible solution. It is expected that narrow track vehicle (NTV’s) would be the solution all for these problems. In many countries a number of alternative commuting vehicle have been developed. NTV’s are the convergence of a car and a motorcycle, i.e. with smaller dimensions and reduced energy consumption and pollutant emission. In this paper the analysis of construction solutions for a narrow track vehicle, considering their stability, safety problems as well as other factors will be presented. The author’s concepts of a narrow vehicle are also presented. Two small narrow cars were designed at CUT.

1. Introduction

At the beginning of the 21th century the general public and the automotive industry continue searching for potential solution to commuting problems and potential improvements in transportation [1, 4]. Taking into account that about seventy seven percent of users exploit their own vehicles for commuting (fig.1) developing the new means of transportation seem to be the necessity.

![Figure 1. Vehicles use in a commuting](image-url)
Users mentality also changes, then they are no longer forced to buy the five-passenger vehicle that constitutes the dominant automotive architecture sold in the world today. Moreover about seventy five percent of all driving is done solo with nothing but a personal bag (fig.2).

![Figure 2. Average vehicle occupancy](image)

Motorbikes, scooters, bicycle have all been consider as valid alternatives to the conventional motor vehicles. This single passenger vehicle is ten to thirty times more energy efficient (fig.3) than private cars or even public transport.

![Figure 3. Comparison of a vehicle exploitation cost](image)

These means of transportation have many advantages when compared to traditional motor vehicles but their lack of comfort, high safety risk and special skill requirements cause the limitation of their use. That the reason why a new type of vehicle is required. The new vehicle generation should combine safety and comfort of a conventional vehicle with small size, low cost, ultra low fuel consumption which are characteristic features of a scooter. It is expected that, a narrow one or two seat vehicle which occupies about half the lane width and half the parking space of a conventional vehicle will be the solution of one of the commuting vehicle problems. One of the ideas of NTV research is to develop a narrow vehicle that seats two people in tandem. However, the narrow track of the vehicle can be the reason for unstable vehicle behavior during cornering. This problem can be mitigated by tilting the vehicle similarly to a motorcycle. More complex problem is the occupants safety. Smaller size and the increased likelihood of roll over is one of the NTV’s disadvantages. Occupant protection in the case of collision can be improved by special frame or body shape. However, probability of roll over increases sharply with increasing ratio of gravity centre height to the wheel track. It is very difficult to decrease the height of centre of gravity because the designer of NTV is constrained by the need to maintain easy accessibility and good visibility. One way of counting
this risk is to bank the vehicle into the turn like the motorcycle. Hence, an inherent tilting mechanism is required. This tilting mechanism should not require any special skill from the driver. Besides tilting capability other desirable features for commuter vehicle include weather proof interior and heating device are required. Since an NTV is to be operated in normal driving conditions its behavior should be similar to the one of a conventional vehicle.

This article presents summary review of other alternative vehicles and presents author’s construction solutions.

2. Alternative commuter vehicles

Alternative mode of transport is needed to meet today’s demand. Examples of alternative small vehicles that were introduced during the last 10 years are mainly single or tandem occupants vehicle with four or three wheels (fig.4). None of them are ideal, but they all give us the knowledge about the technical problems in such a vehicle construction.

![Tango][19]    ![Elio –Motors][12]

![E-lord][20]    ![Colibri][18]

**Figure 4.** Examples of alternative vehicles

Having four wheels means that these vehicles are conventional cars and they could pass the standards for normal car. For a four-wheeled vehicle with equal front and rear track, the maximum achievable lateral acceleration is determined by the ratio of half the wheel track and the height of the centre of mass(fig.5).

![Forces acting on the narrow vehicle][2]

**Figure 5.** Forces acting on the narrow vehicle [2]

The maximum lateral acceleration application before vehicle roll over can be calculated during a steady state turn when normal load $F_z$ equals zero.

The maximum lateral acceleration is expressed by equation:
for four wheel vehicle, and because of a lot of small cars as well narrow cars have the three wheels platform the maximum acceleration is:

\[ a_y = \frac{gT}{2h} \]  

(1)

As \( \frac{a}{L} < 1 \) the resistance to roll-over of a three-wheeled vehicle is less than that of four-wheeled vehicle. The configuration of these vehicles is presented in fig.6.

\[ a_y = \frac{gT a}{2h L} \]  

(2)

Three wheels platform is not as expensive as platform with four wheels. A serious problem appears with the form of vehicle with single wheel in front (delta form). The structure of such a vehicle is very simply, as motorbike parts can be used here. Maneuverability is the advantage of this vehicle. Moreover, the creating car body with small aerodynamic drag is easier than that of a conventional car. Tear drop shape is often used. Cornering and braking are of paramount importance for any vehicle but vehicle with single front wheel is characterized by tendency for roll over during these maneuvers even at slight accelerations. Because of this if we are using three wheels, a reverse bicycle (form tadpole), like Elio-Motors is more successful layout. If rear wheel steering is applied the width of vehicle can be very small but the tendency to rollover becomes higher because the ratio of height of centre of gravity to the wheel track increases. This solution will reduce the vehicle size requirement by so much that a vehicle with a less than one meter track width would be adequate.

Since the narrow track of the vehicle is applied these vehicles are characterized by the tendency to roll over. By tilting the centre of mass towards the centre of the curve, the vehicle’s tendency to overturn is reduced. Figure 7 shows the vehicle with its body tilting into the corner.

The maximum lateral acceleration for three wheeled tilting vehicle is expressed by:

\[ \text{Figure 6. Configuration of three wheels vehicle [7]} \]

\[ \text{Figure 7. Force acting on the narrow tilting vehicle [2]} \]
When the values of lateral acceleration (eq.2 and eq.3) are compared, it can be stated that the value of maximum lateral acceleration is higher for tilting vehicle then for normal three wheeled car. The maximum acceleration is now a function of the tilt angle. Taking into account that tilt angle can reach $45^\circ$, vehicle tilt is useful during cornering.

For narrow vehicle stabilizing the torque vectoring can also be applied. In fig.8 some examples of tilting vehicle are presented.

![Carver][13](1)

![Quadro 4][17](2)

![Mercedes][11](3)

![Toyota i-Road][15](4)

![PiaggioMP3][14](5)

![Nissan Gleider][16](6)

**Figure 8. Tilting vehicles**

Car safety features have always been a priority in automotive industry. All above mentioned cars demonstrate some features that are more or less significant for their safety. It is very difficult to combine the proper passive safety of a car with small car size. The lack of crash zones and roll over protection as well as other safety features typical for normal car could contribute to users heavy injuries during accidents. The active safety systems such as anti lock brakes and electronic stability control have been introduced. Unfortunately, narrow car is more sensitive to side wind than a conventional car. Moreover three wheel cars are sensitive also to forces caused by cornering or braking. However, this alternative mode of transport is safer then scooter or motorcycle.

Parking in cities is becoming more and more difficult and prices to park a car are also growing. It causes user’s preference to buy a smaller car, which is also easier to maneuver in a parking area. It is expected that narrow track car will be the solution of this problem.

There are several reasons why commuting transport is required to become more efficient in the future. One reason is reduction of overall costs for consumer. The second one is due to global warming and the resulting CO$_2$ emission regulations. Small size and light weight commuting car seems to be suitable for these requirements.

Design of a car body should be attractive especially for young people. Commuting vehicle should be more fun to drive or better to drive than a conventional vehicle. Engines with high power are frequently applied in tilting vehicles, so they provide additional fun and thrill while the body is leaning sideways.
Regardless of narrow car configuration due to the small wheel track vehicle tilt seems to be necessary. Tilt stability of NTV can be controlled by either the steering input of the vehicle (STC Steering Tilt Control) or by using an additional tilt actuator (DTC Direct Tilt Control) (fig.9). In a DTC system, the driver wheel steering is directly connected to the front wheel steering mechanism and is not used for tilt control. Based on the speed of the vehicle, the calculated radius of curvature of the path and other variables is designated and the motor tilts the entire vehicle into the curve at an appropriate tilt angle. In a STC system, the driver input is not directly linked to the steering mechanism. This type of control is the same method that is used by bicycle and motorcycle riders to balance the vehicle. The driver indicates his desire to turn, than the control system converts the steering wheel angle into desired tilt angle and actual steer the wheels to tilt the vehicle and to get the turn corresponding to the driver’s steering wheel input.

An STC system is more effective at higher vehicle speeds, at lower speeds the DTC system is dominant.

These systems applied individually or joined together[6] need some sensors (i.e. acceleration sensor) and actuators that is why vehicle cost increases. It is commonly know that the most important consumer purchasing criteria is low price of a vehicle. If it is equipped with active tilting system the price of this car is very high i.e. Carver costs 80.000 $.

The price of free tilting vehicle is much lower the of vehicle mentioned above but driving them requires special skills. Free tilting is a standard way of scooters, motorbikes and bicycle behavior. To follow the desired cornering trajectory the driver has to exert the burs of torques on the handle bar and does not experience any lateral acceleration during cornering [3].

3. Author’s narrow vehicle concepts
Using this analysis the important trends and requirements for a new commuting vehicle can be defined. As the vehicle main usage area will be the cities the maximum velocity can be limited to 45km/h. It allows to drive this car without license and the safety vehicle problems can be easily solve. At Cracow University of Technology two concept vehicles were prepared.

The hybrid small vehicle car named BOMBUS is one of them(fig.10.).

Figure 9. Control systems of tilt stability[5]
Bombus (Bumblebee) is an ultra small hybrid vehicle constructed by students of the Mechanical Faculty at Cracow University of Technology. With its 2m50cm length and 1m20cm width, Bombus has the right dimensions to cruise the city. The width of Bombus allows to occupy a fourth part of parking space only (fig. 11).

![Bombus in parking space](image1)

**Figure 11.** Bombus in parking space

Bombus belongs to the group of L-category vehicles. It is powered by two brushless electric motors (BLDC) fitted to the front wheels and an IC engine fitted to the rear wheel (fig. 12).

![Concept of vehicle and door design](image2)

**Figure 12.** Concept of vehicle and door design

The power for the vehicle is provided by a lithium battery pack which is of 20kg in weight and ensures a range of 25 miles. Built around a light aluminium frame wrapped with plastic panels the Bombus weighs 240kg. The performances when both the IC engine and the electric motors are on are similar to the performances of a typical A-class vehicle. According to EU regulations for L6 vehicle category the maximum Bombus velocity is 45 km/h. A qualified driver’s license is not required to drive this category of vehicles. In this vehicle the driver sits in a central position, with a passenger seat immediately behind. The vehicle door design ensures the second seat to be easily accessible. Since the door opens in a specific way additional space, either at the side or above the vehicle, is not needed. The width of Bombus with opened door does not exceed the vehicle track. The shape of a front part of vehicle frame that is specially developed ensures the user acceleration reduction during frontal crash (fig. 13).

![Front part of Bombus frame](image3)

**Figure 13.** Front part of Bombus frame [10]
This project is unique in terms of its architecture and a suitable design for personal mobility in an age of sustainability and energy efficiency.

As mentioned above by tilting the vehicle centre of mass towards the centre of the curve, the vehicle’s tendency to overturn is reduced. Bombus is a narrow car but it cannot tilt. In a city space motorbikes, scooters and bicycles are considered as the best means of transport. The dimensions of these means of transport, especially width, are very small and it ensures good manoeuvrability to their users. To fulfill the stability requirements the vehicle with such dimensions has to be tilting vehicle. Such vehicle is also developed at Cracow University of Technology. Free tilting system is assumed in order to ensure a low price of vehicle. Main dimensions of this vehicle are shown in figure 14. The width of this vehicle is similar to width motorbikes such as Yamaha Tricity or Piaggio MP3[14]

![Figure 14. The concept of tilting commuting vehicle[9]](image)

The rear wheel is a steering wheel in this vehicle. Owing to this construction small width can be obtained. The aluminum vehicle frame is also developed. To help users to stabilize this vehicle in vertical position the special front suspension is developed.

Frame design solution is presented in figure 13.

![Figure 15. Frame design solution [10]](image)

In this design solution the transverse leaf spring is used. This leaf spring does not work during vehicle leaning. Two coil springs (red in figure) stabilize the vehicle in vertical position. Rear suspension is of “Telelever “type. The electric BLDC 4 kW motor is fitted to rear wheel. As in case of the Bombus according to EU regulations for L6 vehicle category the maximum velocity is 45 kmh. This limited maximum velocity allows decreasing the safety risk of motion.

4. Conclusion
At present there is a small number of alternative commuting vehicles that meet the demands for modern means of transport in big cities. Development of these vehicles is the challenge for designers and engineers. The characteristic features of such new cars such as low cost, small size, safe driving, environmental friendliness, fun to drive are very difficult to obtain simultaneously. To solve these
range of problems that are faced by the industry a number of prototypes of alternative commuting vehicles have been developed. Only a few of them are in mass production. To obtain the commercial success overcoming not only the technical difficulties but also the consumers mentality changes will be required. It seems that narrow tilting vehicles satisfy the future users needs.

Two prototypes have been developed at Cracow University of Technology. Both of them are narrow track vehicles. The width of Bombus vehicle to ensure the stability during cornering is 1.2 m. For commuting vehicle used in cities it is better if the vehicle width does not exceed much the width of tricycle such as Piaggio MP3. However, small wheel track needs applying the tilting system in vehicle. Vehicle structure in such construction solution becomes more complicated but it is necessary for ensuring motion stability. If the rear steering wheel will be employed the vehicle width can be about 0.8m. The other prototype is the tilting vehicle with rear wheel steering. It is expected that this construction solution fulfills the requirements for commuting vehicle.

The advantages of narrow tilting vehicle as the commuting vehicle signify that narrow tilting vehicles are the future of individual means of transport in cities.

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